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Volume XII

TECHNICAL PAPERS FROM THE LENINGRAD INTERNATIONAL SYMPOSIUM ON THE METEOROLOGICAL ASPECTS OF ATMOSPHERIC POLLUTION

PART I

Edited By

M. Y. Nuttonson

The material presented here is part of a survey of
USSR literature on air pollution
conducted by the Air Pollution Section
AMERICAN INSTITUTE OF CROP ECOLOGY

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1972

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PREFACE

The present volume consists of translations of papers dealing with the meteorological aspects of air pollution. These papers were initially presented at an international symposium held in Leningrad during July 1968. In 1971 they were published as a report, edited by Prof. M. E. Berlyand, by the Hydrometeorological Publishing House.

The report contains a total of 40 papers, 37 of which are in Russian and three, in German, together with their accompanying abstracts. In this volume we present a collection of translations of a considerable number of papers from the original report. It is planned to make the remainder available in the near future.

A review article by T. A. Ogneva, "International Symposium on Meteorological Aspects of Atmospheric Pollution" (Izv. VGO*, Vol. 101, No. 4, 1969, pp. 395-396) provides interesting background material regarding the Symposium. For this reason we present our translation of Ogneva's paper in the following paragraphs.

"At the present time, considerable attention is being given to the study of atmospheric pollution in order to improve the sanitary status of water and air reservoirs in urban areas and workers' settlements and to intensify measures aimed at the preservation of nature. In working out the measures designed to decrease the pollution of air by noxious impurities, a special role is played by the consideration of meteorological factors, that substantially determine the behavior (dispersal) of impurities in the atmosphere. This problem was the subject of an International Symposium on Meteorological Aspects of Atmospheric Pollution, held in Leningrad at the A. I. Voeykov Main Geophysical Observatory on 22-31 July 1968. The organizers of the Symposium were the State Committee of the USSR Council of Ministers on Science and Technology (Scientific Council on the Problem 'Protection of the Air Reservoir from Pollution by Noxious Substances') and the Main Administration of the Hydrometeorological Service, Council of Ministers of the USSR.

"The Symposium was attended by scientists and specialists (meteorologists, hygienists, chemists, power engineers, metallurgists, etc.) from Bulgaria, Hungary, Vietnam, the German Democratic Republic, Poland, Rumania, Czechoslovakia, and the Soviet Union. Forty-five reports were delivered, and there was an animated discussion on the subjects of physical principles and methods of calculation of dispersal of industrial emissions in the atmosphere; meteorological parameters determining atmospheric diffusion and intensity of atmospheric pollution; procedures and equipment for observing atmospheric pollution, and experimental studies of pollution of the atmosphere by noxious impurities.

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* Izvestiya Vsesoyuznogo Geograficheskogo Obshchestva, Tom 101, vip. 4, Iyul' - Avgust 1969.

"On the first day, M. Ye. Berlyand (Main Geophysical Observatory) reported on the status and prospects of development of meteorological studies of atmospheric pollution. He noted the following basic problems in the development of further research: study of meteorological conditions in the presence of heavy air pollution, including the mechanisms of turbulent exchange in the presence of inversions, a complex topography, and urban buildings; development of automatic and recording apparatus; study of the vertical distribution of noxious impurities; accumulation of observational data and development of methods of forecasting pollution, etc.

"In the report of I. L. Varshavskiy (State Committee of the USSR Council of Ministers on Science and Technology), 'Basic Trends of Scientific Research on Protection of the Air Reservoir from Pollution', the problems mentioned as the major ones involved the study of the biological action and hygienic importance of atmospheric pollutants, the influence of meteorological conditions on the distribution of noxious impurities in the atmosphere, the removal of noxious impurities from waste gases of industrial enterprises, and the removal of toxic components from the exhaust gases of internal combustion engines.

"Considerable interest was elicited by the report of M. S. Gol'dberg (A. I. Sysin Institute of General and Communal Hygiene) on the 'Hygienic Standards for the Maximum Permissible Content of Noxious Substances in Atmospheric Air.' He noted that hygienic standards worked out on the basis of experiments and actual laboratory and clinical studies constitute the scientific basis of environmental improvement measures in the struggle with atmospheric pollution, and make it possible to evaluate the results from the standpoint of providing the optimum living conditions for the population.

"Papers by a number of members of the Main Geophysical Observatory presented studies dealing with the physical validation of the procedure for calculating the pollution of the atmosphere with emissions of industrial enterprises and steam power plants, an investigation of turbulence in the lower 500-meter layer, an experimental study of pollution in industrial areas on the territory of the Soviet Union, the establishment of the relationship between meteorological conditions and air pollution in urban areas, the development of automatic methods of determination of atmospheric pollutants, etc. There were also reports on studies conducted in collaboration with Moscow University (S. M. Gorlin) in which the influence of irregularities of the earth's surface on the characteristics of the air flow was investigated in wind tunnels in connection with the problem of impurity diffusion.

"Members of the Institute of Experimental Meteorology (USSR) presented a series of reports on the study of diffusion of impurities and characteristics of turbulence from a 300-meter meteorological mast in Obninsk. Individual reports were also delivered by members of the Institute of Applied Geophysics (Ye. N. Teverovskiy), the Central Aerological Observatory (N. Z. Pinus), the

F. F. Erisman Scientific Research Institute of Hygiene (R. S. Gil'denskiol'd and B. V. Rikhter), and others.

"Specialists from Czechoslovakia (A. I. Vesecky, head of delegation), the German Democratic Republic (W. Warmbt, head of delegation), Poland (W. R. Parczewski, head of delegation) introduced the participants of the Symposium to the broad range of experimental research on the problem of atmospheric pollution. D. Szepesi (Hungary) reported on studies of meteorological conditions of turbulent diffusion, and G. I. Diaconescu (Rumania), on studies of thermal stratification of the atmosphere in connection with the pollution problem.

"All the participants of the Symposium came to the conclusion that at the present stage of the struggle with atmospheric pollution, the methods of purification and the construction of high stacks should be combined for the purpose of effectively utilizing the dispersing capacity of the atmosphere.

"The need for an extensive introduction of meteorological investigation of industrial projects and for the forecasting of air pollution was noted. One of the primary problems noted was that of validating and standardizing the methods of calculation of atmospheric pollution, the meteorological and hygienic procedures in studying the chemical composition of the atmosphere, and the meteorological parameters determining this composition."

It is hoped that the papers presented in this volume will be conducive to a better appreciation of the meteorological-air pollution investigations conducted in the USSR and in a number of the Soviet-block countries. As the editor of this volume I wish to thank my co-workers in the Air Pollution Section of the Institute for their valuable assistance.

M. Y. Nuttonson

March 1972

ABSTRACT

M. Ye. Berlyand

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade – Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad – July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 4, - (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

This collection of reports consists of papers delivered at the International Symposium held in Leningrad, at which eminent specialists from different countries summarized the status of research on meteorological aspects of atmospheric pollution.

The papers describe the status and prospective development of this problem, methods of calculating the dispersal of industrial emissions in the atmosphere, results of theoretical and experimental studies of dissemination of harmful impurities in the air, modern methods of determination of concentrations of noxious substances and meteorological parameters determining their transport in the atmosphere. In addition, the papers discuss questions of automation of observations and treatment of the data obtained, statistical analysis of information on the degree of pollution of the atmosphere, study of the influence of local topography on the propagation of impurities, results of wind tunnel experiments, etc.

The collection is addressed to specialists and scientists in the areas of meteorology, aerosol physics and chemistry, atmospheric air hygiene, designing and operation of ventilation and gas-cleaning industrial equipment, aerosol research, etc., and also to students of these disciplines.

INTRODUCTION

M. Ye. Berlyand

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 5-7, - (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The problem of atmospheric pollution has assumed a great urgency in many countries. Despite the tremendous achievements of modern science and technology, the measures taken to insure the purity of the air reservoir have been utterly inadequate. Moreover, atmospheric pollution has become a dangerous by-product of progress in the development of industry, power engineering and transportation. Yet, in a substantial number of cases, the application of the developed methods of air pollution control indicates very definitely that this problem could be solved right at the present time.

An important, perhaps a key role is played by meteorologists who specialize in atmospheric physics and chemistry. Thus, the basic problem of limiting the discharge of noxious emissions into the atmosphere cannot be solved without determining the degree to which such limitation must be implemented, and this is directly related to the evaluation of the dispersal of emissions in the atmosphere. Consideration of the meteorological conditions that completely determine the transport of impurities in the atmosphere is the basis for a correct approach to the organization of measures aimed at air pollution control.

The struggle with atmospheric pollution is increasingly assuming an international character. This is due both to a common interest in the search for effective ways of preventing harmful consequences, and to the fact that the air currents and harmful impurities which they carry know no national boundaries. Cases are knwon in which the influence of pollution sources is manifested not only in the countries where they are located but also in neighboring states. The problems of air pollution control are so complex that their independent solution by individual countries is not always possible or workable. On the other hand, the joining of forces by scientists of different countries should promote the development and efficiency of the work to be done.

One of the steps in this direction has been the International Symposium on Meteorological Aspects of Atmospheric Pollution, held from July 22 to 31, 1968 in Leningrad. The Symposium was organized by decision of the Eighth Conference of Directors of Hydrometeorological Services of Socialist Countries, and held at the A. I. Voyeykov Main Geophysical Observatory.

Participating in the Symposium were 175 experts, including 32 from Bulgaria, Hungary, the Democratic Republic of Vietnam, the German Democratic Republic, Poland, Rumania, and Czechoslovakia. The Soviet participants of the Symposium represented 62 institutions from 19 cities of the USSR.

At the opening of the Symposium, its participants were greeted by: Prof. V. Ya. Nikandrov, from the Main Administration of the Hydrometeorological Service under the Council of Ministers of the USSR and the Main Geophysical Observatory; Academician I. V. Petryanov-Sokolov from the Academy of Sciences of the USSR; Prof. I. L. Varshavskiy, from the Scientific Council on Protection of the Air Reservoir from Pollution by Noxious Substances under the State Committee of the Council of Ministers of the USSR on Science and Technology, and M. K. Nedogibchenko, from the Health Ministry of the USSR. The welcoming addresses noted the great importance of the problem of achieving atmospheric purity and the crucial part played by meteorologists in its solution.

The Symposium meetings were topical in character. They included the discussion of the following questions:

1. Physical principles and methods of calculation of dispersal of industrial emissions in the atmosphere.

2. Meteorological parameters determining atmospheric diffusion and degree of air pollution.

3. Experimental studies of air pollution by noxious impurities and results of observations.

4. Procedure and instrumentation for observations of atmospheric pollution.

The papers delivered made it possible to exchange the research experience of different countries and summarize the initial results of work on the meteorological aspects of the problem of protecting the atmosphere from pollution. The success of the Symposium was fostered by the fact that in addition to meteorologists, other active participants were experts in related branches of science, i.e., hygienists, technicians, and builders.

The Symposium adopted a resolution stating that the papers delivered attested to the success achieved in the development of a theory of atmospheric diffusion and in development of methods for calculating the dispersal of industrial emissions, in the study of turbulent characteristics, and in the formulation of experimental investigations, including the development of methods and instruments for observations of atmospheric pollution. At the same time, the study of many problems has only begun. In the view of the participants of the Symposium, further studies should follow the line of investigation of the meteorological conditions under which heavy atmospheric pollution is observed, in particular, evaluation of turbulent exchange in the presence of temperature inversions, and study of air currents associated with a dissected topography and built-up urban areas. There is need for the development of methods of evaluating average concentrations for long periods of time and methods of forecasting air pollution. It is also necessary to design automatic and recording apparatus that will be available for practical application on a large scale.

The solution of these problems requires a large variety of theoretical and experimental studies, and thus their coordination and the cooperative efforts of those who will perform the studies are highly important.

With this in mind, the participants of the Symposium turned to the Conference of Directors of Hydrometeorological Services of The Socialist Countries with a number of recommendations of a scientific-organizational nature. The recommendations state the need for expanding cooperative scientific research, conducting studies on bilateral agreements between individual countries, exchanging experts for the purpose of familiarization and participation in the work being carried on, creating a working group of experts on meteorological aspects of atmospheric pollution, conducting studies on the standardization of the methods for calculating the dispersal of industrial emissions and also of the procedures and instrumentation used for the observations, periodic convening of international symposia, and organizing colloquia on special aspects of the problem.

Reports on the Symposium, published in a number of journals, have elicited considerable interest in it in international scientific circles. It may be presumed that the publication of reports of the Symposium will promote international cooperation on one of the most pressing problems of today, the protection of the air reservoir from pollution.

The papers at the Symposium were delivered in Russian, German and English. The papers delivered in German have abstracts in Russian, and those given in Russian have abstracts in English.

The preparation of this collection for printing enlisted the participation of the following members of the staff of the A. I. Voyeykov Main Geophysical Observatory: N. Sh. Vol'berg, Ye. L. Genikhovich, A. S. Zaytsev, T. A. Ogneva, R. I. Onikul, O. P. Petrenchuk, and S. Z. Sorits.

STATUS AND PROSPECTIVE DEVELOPMENT OF METEOROLOGICAL STUDIES OF ATMOSPHERIC POLLUTION

M. Ye. Berlyand (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of
the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty
Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom
simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad -
July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.)
Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 11-23, (1971). (Hydrometeorological Publishing House,
Leningrad, (1971).)

The rapid increase in discharges into the atmosphere of noxious substances that are a dangerous by-product of progress in man's industrial activity has made it necessary to develop air pollution research in many different countries.

According to incomplete available data, tens of millions of tons of ash, sulfur dioxide, etc. are discharged into the atmosphere every year. However, no matter how great the amount of substances discharged into the atmosphere, the danger is not posed by their sum total alone. The volume of the atmosphere or air reservoir into which they can penetrate is enormous. For this reason, their concentrations are not always high. The main danger lies in the localization of discharges near the Earth's surface, in the layer near the ground where vital activity takes place, and the problem is not so much the amount of impurities discharged as their distribution in space and time. The distribution is completely determined by meteorological factors. This accounts for the serious difficulties which must be overcome in solving the problem of achieving purity of the air reservoir by meteorological means. This applies both to the organization of an efficient system of control of the degree of atmospheric purity, and to the implementation of steps toward reducing the hazards related to industrial emissions.

Still, no adequate attention has been given for a long time to the consideration of meteorological conditions in the planning and operation of industrial enterprises. As a result, the concentration of noxious substances in the surface layer in some populated centers had become so large that it was necessary to move the industrial facilities and sometimes entire towns.

Systematic studies of the meteorological aspects of atmospheric purity began relatively recently. However, the scientific principles on which they were developed were laid down gradually over a long period of time. The main studies of atmospheric turbulence and atmospheric diffusion of impurities include those of H. Taylor, A. A. Friedman and L. V. Keller, and also a large body of research carried out in many foreign countries and in the USSR by scientists of the Main Geophysical Observatory, Institutes of Atmospheric

Physics and Applied Geophysics, and Leningrad Hydrometeorological Institute. A review of many of these studies is given in [26], [29a] and [37a].

Studies by Sutton and Bosanquet and Pierson, carried out in the 1930's and 40's, have been widely applied in practice. They served as the basis for the initial attempts to standardize industrial emissions into the atmosphere by taking into account certain meteorological characteristics. Subsequent studies, including the first practical investigations made in the USSR, used essentially a few modified formulas proposed by Sutton. However, experiments showed that these formulas were chiefly a qualitative expression of certain characteristics of propagation of impurities in the atmosphere. Quantitatively, however, there frequently arose discrepancies amounting to factors of 3-5 and sometimes 10-15 between the observed and the calculated data.

Practice gave rise to new requirements for studies of atmospheric diffusion. It was necessary to investigate the conditions of impurity dispersal up to more elevated levels above the underlying surface and at greater distances from the sources than in earlier studies. The consideration of meteorological factors had to be more extensive and rigorous without being confined to land-based data on the wind velocity alone, as had been the case earlier. There was need for the development of a theory of turbulent diffusion for a layer several hundred meters thick, taking into account possible variations of temperature, wind, and exchange coefficient. In addition, it became necessary to switch from featureless landscape conditions, which usually served as the reference for the preceding studies, to actual topographic forms, taking into consideration the irregularities of the underlying surface, and also to the development of methods of observation and discription of atmospheric pollution over large areas, under urban conditions, etc.

The existing potential for conducting these studies lay in the development of a theory of atmospheric diffusion based on the solution of the equation of turbulent transport of impurities discharged by sources. In contrast to the other trend of empirical-statistical description of diffusion widely exploited at the present time, this trend is more universal and permits one to solve the problem for different sources and different characteristics of the medium and boundary conditions. It enables one to make use of the turbulent exchange parameters employed in studies of heat and moisture exchange.

A new approach along these lines has been developed in the last few years at the A. I. Voyeykov Main Geophysical Observatory [17]. It consisted in taking into account that the coefficients of the atmospheric diffusion equation are generally complex functions of the coordinates, particularly in the study of a boundary layer of the atmosphere several hundred meters thick in the presence of elevated inversions, in the study of hilly terrain conditions, etc. This called for the development of numerical integration methods involving extensive use of electronic computers and for the overcoming of difficulties in the physical formulation of the problem.

One of such difficulties is that in calculating concentrations from comparatively high sources at large distances from the source, the effect of eddies of different magnitudes on the horizontal dispersal of impurities is substantial. The horizontal component of the exchange coefficient effectively increases with the distance from the sourcs, and this gave rise to complications in the interpretation of the results obtained. In order to overcome this difficulty, the variation of the wind direction with time was considered, and the appropriate averaging of the concentrations was carried out.

Another difficulty arose because the gases originating from the stacks have an initial entrainment velocity and are frequently overheated relative to the ambient air. As a result, near the sources of emission, and sometimes over large distances, a field of vertical velocities is produced, which damps out with increasing distance from the source and promotes the upward ascent of the impurity. This velocity field can be determined by solving a system of equations of motion and heat inflow which describes the propagation of a heated jet in an entraining flow in the general case. The use of numerical integration methods makes it possible to take into account the spatial velocity fields obtained in the equation of turbulent diffusion [10]. To get an approimate evaluation of the initial ascent of the impurity, one can introduce, as is usually done, a certain effective rise of the source. Since the magnitude of this ascent is a function of the wind velocity, there exists some dangerous wind velocity at which the highest value of the ground concentration is reached.

On the basis of the solution obtained, formulas were derived and schemes worked out for calculating these values for both individual sources and groups of sources [8, 12], etc.

It follows from the formulas that under the same conditions of impurity emission, the maximum concentrations turn out to be different in different climatic zones, in particular, high for southern and forested regions, where an intense vertical turbulent exchange takes place. The maximum concentrations depend substantially on the settling rate of the impurity. They are therefore greater for dust than for gases, and more so the coarser and heavier the dust particles. Other things being equal, for industrial emissions, the concentration maxima of a heavy and of a light impurity differ by a factor of 2-2.5. The studies performed showed that the difference also depends on the height of the source and may reach large values at source levels higher than 300 m. The working formulas were obtained for comparatively frequent unfavorable meteorological conditions. They are characterized by the fact that the temperature drops with the height, and the wind velocity changes approximately in accordance with the logarithmic law. In addition, the degree of turbulent exchange is substantial, and the impurity is transported from high sources down to the surface air layer.

The theoretical studies performed [7, 9] showed that surface concentrations may reach even higher values. In the presence of elevated inversion layers with an attenuated turbulence located directly above the source, the concentration maximum is sometimes doubled. In cases where such a layer is 100-200 m higher than the source, the concentration increase is appreciably smaller. The presence of elevated inversions may cause a much greater effect in the case of cool emissions. Our studies [4] show that cool emissions into an air layer with a temperature inversion, independently of the wind velocity, cannot rise above a certain height. For this reason, the ground concentrations in such cases increase sharply in the presence of weak winds.

Occasionally, appreciable deviations are observed in the vertical wind profile from the logarithmic profile, which applies mainly to average conditions. The studies performed [10] showed that when a calm is present near the ground, the ground concentrations increase, and do so more markedly the thicker the still layer.

These anomalous cases of temperature and wind distribution show a greater frequency under urban conditions. Thus, in the presence of deep inversions outside a town, as is the case at night, particularly in the winter, a so-called heat island is observed within the town, the inversion in the lower layer breaks down, and is retained only above the town's buildings. Within the built-up urban area the wind also frequently dies down to a calm, whereas above, in the free stream, the wind intensifies.

This group of problems is associated with the development of the theory of dissemination of an impurity in the presence of fogs [11]. Under urban conditions, there is a mutual reinforcement of the action of fog and air pollution. Industrial and domestic aerosols promote the condensation of moisture. In the presence of a fog, some impurities, particularly sulfur dioxide, become more toxic themselves. Particularly serious consequences of air pollution are attributed to fogs and their modification -- smogs. The calculations performed in [11] revealed important effects indicating that in addition to a redistribution of noxious substances as a result of their absorption from air by water droplets, there takes place an increase in the ground concentration, due to an intensification of the transport of these substances from a region located above the fog layer.

In the presence of topographic roughness, movements of air are produced that may lead to considerable concentration changes. The use of modern methods of theoretical study of atmospheric diffusion with the aid of electronic computers has made it possible to handle the solution of these difficult problems as well. Thus far, calculations have been made for a series of characteristic conditions of hilly terrain [10, 13, 14]. It was found that under such conditions, the maximum of the surface impurity concentration is mostly higher than over level ground. This is sometimes observed even when the stacks are located on elevated points near the leeward slope, where the wind velocity decreases sharply and ascending currents arise. Analysis showed that in the case of gentle topographic forms, the air stream flows around them and the increase in concentration is for all practical purposes slight. The influence of a rolling topography is manifested in areas where the wind velocity changes substantially at a fixed height. In this connection, a major importance is assumed by a microclimatic survey of the terrain.

At the present time, this work is developing in two new directions:

numerical studies are being carried out on the equations of motion describing the structure of an air stream under dissected topography conditions [13, 19], and at the same time, experimental studies are being conducted in collaboration with the Mechanics Institute of Moscow University in a wind tunnel with models of rolling topography and various types of urban buildings [20]. The experiments are set up under close to self-similar conditions, which make it possible to extend the simulation results to atmospheric processes. Both the theoretical and the experimental studies permit one to determine the field of vertical and horizontal velocities of motion which are used for the numerical integration of the diffusion equation. Similar methods were also used for evaluating distortions of the impurity field caused by the water reservoirs usually created in the vicinity of electric power plants and major enterprises [14].

In order to check the theory and obtain the necessary parameters, major experimental studies were conducted [3, 19, 21, 22, 27]. The spreading of heated impurities -- ash and sulfur dioxide -- was studied around steam power plants with high smokestacks, and the dispersal of comparatively cool emissions -- hydrogen sulfide and carbon disulfide -- around synthetic fiber plants. Expeditions measured impurity concentrations at distances up to 15-20 km from the stacks, and determined the magnitude of the discharges, and also the entrainment velocities and the temperature of the effluent gases. Observations of the vertical distribution of the meteorological elements to a height of several hundred meters were also made. Measurements near the ground were conducted on telescopic masts, and at higher levels by means of a captive balloon, light airplanes and helicopters. In addition, a systematic photogrammetry of the smoke plume was carried out together with a determination of its parameters from an airplane and a helicopter, in particular, of the plume width at different distances. Instruments are now being constructed for the photogrammetry of smokes, and also a laser device that will permit the determination not only of the boundaries of the visible outline of a plume, but also of its structure, size of the smoke particles, etc.

The studies are complex in character and have involved the participation of various types of organizations, i. e., meteorological, sanitary, and technical ones. It should be pointed out that this group of studies is one of the most complete of all those known to us in world practice. Among analogous studies in socialist countries we can mention the study of air pollution in the vicinity of electric power plants in Czechoslovakia, Hungary, Poland [34, 36, 37, 39], etc; a procedure for the photogrammetry of a smoke cloud, developed in the German Democratic Republic (GDR), also deserves serious attention [35].

In many countries, in experimental studies of atmospheric diffusion patterns, experiments are set up which involve the dispersal of so-called tracer impurities from high masts over both open terrain and towns. Extensive studies were carried out in the U. S. A. [33] under the "Prairie Grass" and "Green Glow" programs and in the GDR by dropping a tracer from a captive balloon to investigate the conditions prevailing over terrain where an atomic reactor was under construction [35].

Research of analogous nature has been conducted at the Institute of Experimental Meteorology on a 300-meter meteorological mast [25, 16]. In the experiment, luminescent powders collected on plane tables located around the mast were dropped from different levels. At the same time, the vertical distribution of meteorological elements was recorded with instruments mounted on the mast.

The conclusions of the theoretical studies discussed earlier were confirmed by the findings of these experimental investigations and also by less detailed sanitary surveys of areas around a number of electric power plants and enterprises.

On the basis of the findings of theoretical and experimental studies carried out by the Main Geophysical Observatory with the participation of the Institute of Applied Geophysics and F. F. Erisman Institute of Hygiene, a "Temporary Procedure for Calculating the Dispersal in the Atmosphere of Emissions From Stacks of Electric Power Plants" was developed [18], then an improved procedure was prepared and "Recommendations for Calculating the Dispersal in the Atmosphere of Pollutants Contained in Industrial Emissions" were compiled [31]. These recommendations were approved by the Gosstroy SSSR (State Committee on Construction of the Council of Ministers of the USSR) and printed on a mass scale as standard documents. In the new recommendations, the scope of application of the working formulas is extended, practical methods of calculating concentrations from groups of sources are proposed, and recommendations are given for determining the distances from the enterprises to the boundary of the sanitary protective zone.

Use of the elaborated procedure will make it possible to achieve an adequate air purity and simultaneously determine the economically most advantageous set of measures for doing so [6, 12], etc. In particular, it is recommended that the emissions be discharged through the smallest possible number of stacks. This feature alone may yield considerable savings. Thus, many enterprises erect several dozen stacks. Their reduction by a factor of 8-10 will not only lead to a substantial decrease of construction costs, but also, other things being equal, will cut the maximum concentration by approximately one-half.

It is important to achieve an optimum combination of the gas purification required and choice of stack height. It must be borne in mind that the maximum surface concentration of heated impurities is inversely proportional to the square of the stack height. This means that an increase of the stack from 10 to 100 m is equivalent to a nearly perfect purification of 99%. Hence the danger of so-called unorganized discharges, i. e., outside the stacks, through windows and cracks of the industrial buildings. Although the volume of such discharges is much smaller than that of organized ones, they may produce very substantial concentrations in the surface layer, since they occur at samll heights.

Despite the comparatively large number of formulas frequently employed in different countries for calculating the dispersal of impurities, there are few standard methods of this type that have been approved as standard documents.

Let us now consider some aspects of the organization of control of atmospheric purity. Points of observation of air pollution have now been set up in many urban areas throughout the world. In some cities, an experimental network including about 100 or more such points has been organized. In the USSR, observations have been conducted at sanitary-epidemiological stations for a relatively long time. Recently, a network of hydrometeorological service posts has been organized in many urban centers. At these posts, systematic measurements of the concentrations of the main ingredients and meteorological elements are made several times a day. Special pavilions are set up for the observations. Studies are being made to use automatic recording gas analyzers for this purpose. An automatic sulfur dioxide concentration recorder has now been constructed in the USSR [2], and research on analogous instruments for the main ingredients is being carried on. Similar instruments are being worked on abroad, including countries of the socialist camp. It is of interest to compare the readings of these instruments and to consider a possible standardization of the methods of observation.

Work has now been started in the USSR on the use of such instruments in motor vehicles and helicoptors [23]. Initial results have been obtained from observations of the distribution of some pollutants over a city, and the findings turned out to be similar to those obtained relatively recently over Budapest [35].

The massive data of observations made in cities are subjected to statistical analysis. Despite the inhomogeneity and insufficiency of the initial data, their sum total is of interest and makes it possible to draw a number of conclusions concerning the patterns of variation of the concentrations [5, 29, 30].

The heaviest air pollution is of course observed in major industrial centers. Moreover, analysis of the observational data indicates that urban air is most heavily polluted in areas with unfavorable meteorological conditions. A clear-cut influence of climatic factors is manifested in the analysis of the annual variation of the maximum concentration and recurrence of days with concentrations in excess of the permissable ones.

In many cities, the maximum air pollution is observed in summer in the presence of an intensive turbulent exchange. Such results were obtained [29], in particular, for dust and sulfur dioxide, a considerable part of which reached the atmosphere as a result of fuel combustion. And, despite the fact that in the summertime the fuel consumption is much less than in winter, the concentrations of dust and sulfur dioxide frequently prove to be higher in the warm half of the year because of the influence of weather conditions. Of great interest is the study of weather conditions under which high concentrations are observed at a majority of the points in a city. Frequently, in conformity with theoretical conclusions, such conditions, are noted in anticyclonic weather, in the presence of inversions over the city and a weak wind in the surface layer.

As industry grow, the zones of atmospheric pollution expand considerably. At the same time, the background concentrations, whose origin is related to the action of natural processes, also increase. In this connection, studies are being made on the spreading of dust and its inorganic and organic components over the territory of the USSR [1, 5, 6], the distribution of condensation nuclei [28], and also the chemical composition of the precipitation falling with deposits of chlorides, sulfur, and some other elements [24].

In summary, it may be stated that atmospheric diffusion and air pollution are being studied along a wide front.

The research methods employed are based on a variety of instruments of modern science. These include computers, precision electronic intruments for recording and processing the observational data, photogrammetry, radar and lasers, gas analyzers, wind tunnel simulation, use of aeronautical engineering, etc. They indicate the great capacities and high level of modern meteorological studies.

Nevertheless, work on the solution of many problems has only begun. Further development should be associated with a more detailed description of the meteorological conditions under which heavy air pollution is observed. This applies particularly to the evaluation of turbulent exchange in the presence of inversions and to the study of air currents under complex topographic conditions and in the presence of urban buildings

At the present time, there is need for the development of methods for evaluating average concentrations over long periods of time. In addition, the corresponding criteria of the danger of prolonged air pollution to living organisms and the environment should be perfected, and the existing differences between the values of one-time and mean daily maximum permissible concentrations should be eliminated.

In the area of experimental studies, further research is needed on the design of automatic and recording instrumentation that is sufficiently versatile and precise while being accessible for wide introduction into practice. The accumulation of observational data should promote the use of physicostatistical analysis of air pollution and the development of methods of forecasting atmospheric pollution in cities with large numbers of pollution sources. There also is need for the development of studies of air pollution due to motor transport and blasting, particularly in deep quarries, and for the study of air pollution at industrial sites and of vertical distribution of noxious pollutants in the vicinity of enterprises, for which a special supply of clean air to industrial buildings is required.

Next in line are studies of the macroscale effects of the spreading of impurities of artificial and natural origin. The transport of noxious pollutants over dozens of kilometers is already being observed, and in some countries, industrial plants pollute the air not only of their own country, but also of other countries. With the existing tendency of cities to expand and merge, vast areas with a polluted atmosphere may be created. Thus there is need for an intelligent evaluation of the expected danger and for recommendations aimed at avoiding it.

In conclusion, let us note that the methods of study of atmospheric diffusion find applications in the solution of various scientific and practical problems. The development of these methods will promote the efficiency of aerosol methods of treatment of farm crops by means of automobile and airplane generators. The evaluations performed show that the consideration of weather conditions and a certain reduction in the flying level of the airplane may cut by almost one-half the area of dissemination of herbicides and other chemicals whose presence on adjoining fields is undesirable, and also promotes an economical consumption of chemicals in field treatment. The use of the elaborated methods of turbulent diffusion will also foster a rational realization of an active influence on atmospheric processes, in particular, in relation to the control of frosts and in relation to the dispersal of fogs and clouds.

The success of the solution of the indicated problems depends considerably on the joining of efforts of meteorologists, technicians and hygienists and on the collaboration of scientists in different countries.

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M. E. BERLYAND

THE STATE AND PERSPECTIVES OF THE DEVELOPMENT OF METEOROLOGICAL INVESTIGATIONS OF AIR POLLUTION*

The rapid increase of pollutant emissions in the atmosphere caused by industry and energetics growth demanded significant development of air pollution investigations in many countries. At present, methods of theoretical and experimental studies of pollutant distribution regularities in the atmosphere and of determination and analysis of the factors stipulating the atmospheric diffusion processes are developed widely.

The results of modern investigations of turbulence and physics of ground air layer and the employment of electronic computer contribute substantially to the development of atmospheric diffusion theory. The numerical integration of turbulent diffusion equation for different kinds of sources at observed wind velocity distributions and exchange coefficient in the atmosphere is carried out. For the purpose of calculation of initial plume rise, characteristic for industrial sources, the system of differential equations describing atmospheric diffusion and convective transfer processes in the presence of overheating and initial velocity of pollutant motion is integrated. The studies of regularities of light and heavy pollutant distributions are carried out, including those in the presence of elevated inversions, calm layers, fogs, etc. The peculiarities of diffusion over hills and

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* Editor's note: The abstract is presented as given in English with the original Russian article.

hollows of underlying surface and near water surfaces are studied. The methods of calculation of air pollution from multiple sources are worked out.

The theoretical investigations are supplemented substantially by a broad complex of expeditionary works in the region of powerful emission sources of heated gases and comparatively cold ventilation gases (near power stations, plants of artificial fibre, etc.). At the same time observations are carried out of emission characteristics and pollutant concentration field at the distances of 10—20km from the source and of meteorological elements near ground defining pollutant transfer conditions in the air layer up to the height of some hundred metres. The experiments in wind tunnels on air current modelling over the hilly terrain and in the conditions of town constructions are organized. Experimental works on pollutant dispersion from high masts are carried out. The obtained experimental data are in good agreement with the results of theoretical investigations.

The observation program for the purpose of air cleanliness control is fulfilled in many cities. It provides for systematic measurements, along with meteorological observations, of concentrations of principal noxious ingredients several times a day. For this purpose, the works are conducted on using automatic recording gas analyzers and instruments put on cars and helicopters.

The mass observation material undergoes statistical analysis; on its basis the role of meteorological factors and air pollution peculiarities is cleared up under different synoptic situations; the methods of obtained information generalization are developed and approaches to forecasting of air pollution level are outlined.

The methods of dispersion calculation of emissions from the stacks of power stations and industrial plants in the atmosphere are worked out on the basis of conducted investigations. The suggested methods include practical recommendations on rational and economically profitable means of securing atmospheric cleanliness.

The further development of investigation can be connected with more detailed characteristics of meteorological conditions at which intensive air pollution is observed. This refers, in particular, to the turbulent exchange characteristics in the presence of inversions, air currents, and turbulence in the conditions of complex relief, town constructions, etc. The development of methods of mean concentration evaluation for long periods of time is needed; at the same time corresponding criteria of danger of continuous air pollution for living beings and outer environment must be improved. In the region of experimental investigations further works are needed on creating automatic and recording instruments, universal enough and available for wide introduction in the practice. The accumulation of observation materials must contribute to the employment of methods of physico-statistical air pollution analysis and to the development of methods of air pollution forecast in big cities with multiple sources. It is also necessary to develop the investigations of air pollution produced by motor transport and during explosion works, the study of vertical distribution of noxious substances in the region of industrial plants, etc. Investigations of macroscale effects of distribution of pollutants of artificial and natural origin are also to be studied.

The methods of atmospheric diffusion investigation are widely adopted for the solving of different scientific and practical tasks. The development of these methods can contribute to the increase of effectivity of aerosol methods of agricultural crops cultivation with the help of aircrafts, to the rational use of artificial modification of atmospheric processes, in particular, for struggle with frosts and dispersion of fogs and clouds.

EFFECT OF THE STABILITY OF THE ATMOSPHERE ON THE DISSEMINATION OF GASEOUS POLLUTANTS

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 24-30, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The State Hydrometeorological Institute of the People's Republic of Poland in Warsaw has a special section of atmospheric pollution research including two laboratories, one dealing with the chemistry of the atmosphere and the other with industrial pollutants. The former is conducting studies on pollution of the atmosphere with sulfur dioxide and carbon dioxide. The industrial pollution laboratory is concerned with theoretical studies of the laws of dissemination of industrial emissions in the atmosphere and also conducts observations of air pollution at seven points.

Plans are being made to carry out measurements of sulfur dioxide concentration in the second half of 1968 in the Warsaw area, using a procedure proposed by K. Budzinski. The purpose of the studies will be to investigate the space and time variability of the concentration of this ingredient. The measurements will be conducted at points located at the nodes of a grid measuring 2 x 2 km, and the observation periods, allowing for the variable character of the change in pollutant level, will be determined by means of tables of random numbers. At each of the points, 15 measurements will be made in the course of a year. The air pollution in one square of the grid (4 km^2) will thus be characterized by 60 measurements at its apices. Analysis of the results is to be performed with the aid of electronic computers and will involve the determination of average concentrations, standard deviations, etc. An experimental study of the concentration distribution functions will permit an evaluation of the probability of occurrence of different values of sulfur dioxide concentrations.

Field studies will be conducted with the aid of a specially equipped motor car on which will be mounted equipment for simultaneous measurement of the principal meteorological elements and 20-minute sulfur dioxide concentrations. A single team will be able to conduct observations over a polygon 700 km^2 in area.

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Preliminary estimates indicate that such organization of the work will be more economical than the use of continuous measurements at stationary points. Similar future studies are proposed over several polygons in different areas of Poland.

The applied climatology section of the State Hydrometeorological Institute is working on an atlas of applied climatology. This atlas will include data not available in general climatic atlases, yet indispensable for justifying the location of industrial plants. These are chiefly annual, seasonal and monthly maps and synoptic tables on the frequency and duration of calms and weak winds with velocities not above 2 m/sec. On the basis of these data for the ground and 100, 200, 300, 400 and 500 m levels, one can evaluate the duration of periods of weak air movement, during which there is a threat of heavy air pollution. The atlas will contain data on the characteristics of the vertical thickness and intensity of inversions in the lower layers of the atmosphere. It will show the number of hours per month with a stable, equilibrium and nonequilibrium state of the atmosphere. A special scheme using indirect aerological methods has been developed for determining these characteristics. Eight types of weather are distinguished, for each of which nocturnal and diurnal vertical temperature distributions have been established. The type of weather observed in a given period is determined by analyzing the results of observations from weather stations, ground synoptic maps and results of radio sounding at the closest points. Correlation of these data will make it possible to plot maps of the state of stability of the atmosphere. Use of the atlas will reduce the volume of meteorological data to be processed when industrial enterprises are planned.

Let us consider the influence of atmospheric stability on air pollution on the basis of observational data on sulfur dioxide concentrations near a steam power plant in Skawina (in the south of Poland). When the stratification was stable and the wind velocity at the stack orifice was up to 4 m/sec, the average concentration was about 0.13 mg/m^3. When the wind intensified to velocities above 4 m/sec, the average concentration was about 0.07 mg/m^3, i.e., decreased by a factor of approximately 2. The maximum concentrations were frequently observed relatively far from the source. Thus, on 24 October 1961 at a distance of 1.5 km, the sulfur dioxide concentration was 0.05 mg/m^3, and at a distance of 4.5 km, 0.10 mg/m^3. When the state of the atmosphere is stable, only slight fluctuations of the concentrations are usually observed. During periods of unstable stratification, the concentrations fluctuate sharply in the daytime, and the fluctuation period is several minutes long. During periods of short-term increase, the concentrations reached values of 0.3-0.8 mg/m^3, i.e., sometimes exceeded the permissible value of 0.5 mg/m^3 (Fig. 1). It is important to indicate that these fluctuational increases in sulfur dioxide concentrations recurred very regularly. They may be attributed to descending air currents of fluctuational character. Under the conditions prevailing in Poland, an average of 70% of days with unstable stratification are observed [2].

Depending on whether the unstable state is weak, moderate, or strong, which in turn depends on the wind velocity and intensity of solar radiation, the periods of fluctuations on the plume axis vary from 10 to 30 min [3]. At the edge of the smoke plume the concentrations are more uniform in time, although even in these cases, concentration fluctuations are still observed (Fig. 2). This pattern is also confirmed by data of almost 7 hours of continuous measurements of SO_2 concentrations. These measurements were conducted in the west of Poland in the area of the Turoszow Electric Power Plant by means of an EEL-SO_2 meter from 10 to 11 July 1962 in still and clear weather, while a surface temperature inversion was being formed.

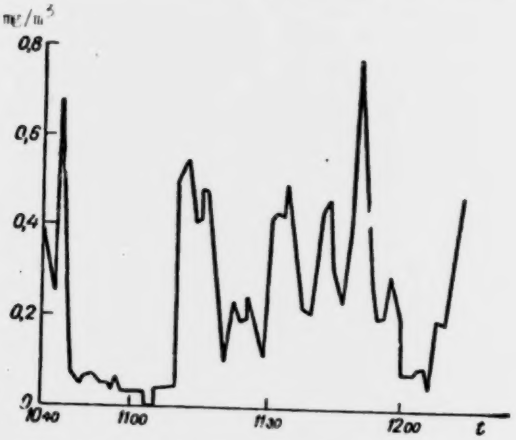

Fig. 1. Variation of SO_2 concentration in the presence of unstable stratification in the area of the steam power plant in Skawina, 21 June 1961.

In the presence of such a definitely stable state of the atmosphere, in the course of 5 hours, the average concentration was 0.1 mg/m^3 (Fig. 3), and the slight fluctuations were apparently caused by oscillations of the smoke plume and by the influence of the background pollution originating from sources near the ground. At about 8 A.M., turbulence and vertical currents began to develop intensively. As a result, the sulfur dioxide concentration near the surface of the ground began to fluctuate strongly from values of almost zero to 0.3-0.4 mg/m^3, and toward the end of the observations, to 0.7 mg/m^3 (Fig. 4). The fluctuation periods amounted to about 10 minutes between 8:20 A.M. and 9:50 A.M. and 15-20 minutes between 10:40 A.M. and 11:30 A.M. Other investigators also observed regular fluctuations of sulfur dioxide concentrations in the presence of an unstable state of the atmosphere, but did not attribute them to vertical fluctuations of thermal currents.

As follows from the above, data on the stability of the lower layer of the atmosphere are very important in the study of the influence of meteorological factors on the dissemination of industrial emissions. One of the

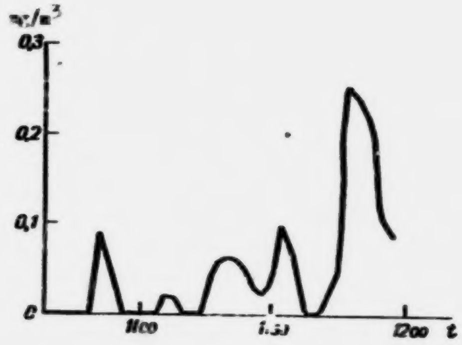

Fig. 2. Variation of SO_2 concentration in the presence of unstable stratification, when the measuring instruments were located at the edge of the smoke plume at a small distance from it in the area of the Skawina steam power plant, 26 May 1961.

most accessible methods that can be used for readily evaluating the state of atmospheric stability almost anywhere is the observation of smoke plumes.

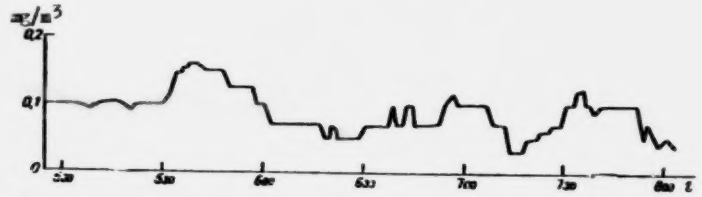

Fig. 3. Variation of SO_2 concentration in the morning in the presence of stable stratification in the area of the Turoszow steam power plant, 11 July 1962.

To make the observed results comparable, it is necessary to establish an international standardization of the classification of these plumes, patterned after the existing classification of clouds. In our view, such a classification should take into account the dependence of the plume shape

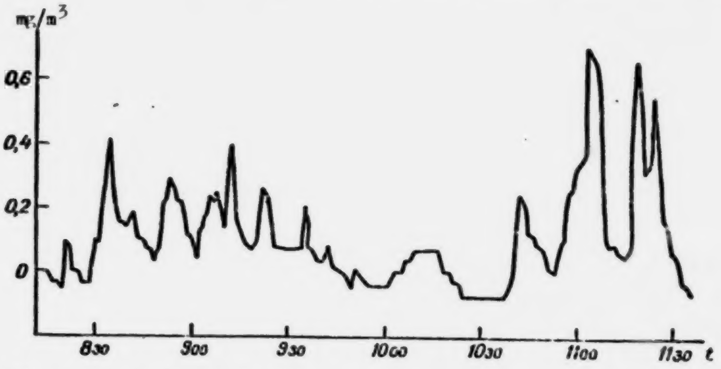

Fig. 4. Variation of SO_2 concentration throughout the day in the presence of unstable stratification in the area of the Turoszow steam power plant, 11 July 1962.

on the stability of the atmosphere and wind velocity at the level of the smokestack orifice. Although the latter factor is very important, it is not considered in many classifications. At low wind velocities (up to approximately 4 m/sec), a smoke plume looks quite different in unstable and stable stratification. In the presence of a stronger wind, the smoke plumes for different stratifications become more similar, and only thorough observations permit the identification of certain differences in their shape. Such studies should yield additional information on local weather conditions in areas of major industrial plants. Moreover, without additional financial investments, the number of points of vertical sounding of the lower atmospheric layers would be increased many times.

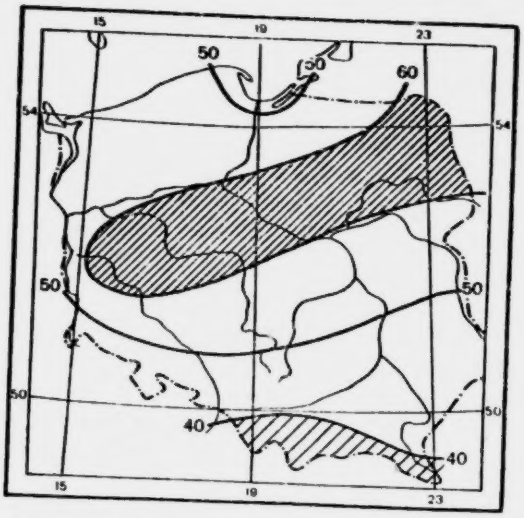

Fig. 5. Average duration of unstable stratification in Poland in June (% of total number of hours per month).

In order to put the findings to practical use, it is necessary to obtain at least tentative data on the duration of different types of stratification over the territory of the entire country. The duration (in percent) of an unstable, neutral and stable state of the atmosphere in Poland was calculated by using methods of indirect aerology. For this purpose, surface weather maps, the state of the weather and stratification curves at selected weather stations were analyzed according to the accepted classification [1]. The reliability of the analysis performed was confirmed by observational data for the closest point of radio sounding.

As an example of the results obtained, one can take a map of the average duration of unstable stratification in Poland in June for many years (Fig. 5). As follows from the map, the duration of unstable stratification is considerably differentiated in different areas of Poland. The treatment includes similar maps for the entire year, individual seasons, and months, for all types of stability.

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V. PARCHEVSKY

ON THE INFLUENCE OF ATMOSPHERE STABILITY ON GASEOUS POLLUTANT DISPERSION*

A brief description of investigations carried out by the State Hydrometeorological Institute of Poland and aimed at studies of air pollution and meteorological factors determining it, is given. The works are performed in the following directions: theoretical investigations of regularities of industrial smoke dispersion in the atmosphere; experimental study of air pollution in the cities and in the regions of power stations; compilation of applied climatology atlas generalizing data on calms, temperature inversions, types of lower air layer stability, etc., necessary for plant projecting and not contained in general climatological atlases. An investigation complex is described which was planned to be carried out in the second half ot 1968 on a special training ground in the region of Warsaw. It was supposed to fulfil sampling and meteorological observations with the help of specially equipped car, and evaluate spatial and temporal concentration variation, etc.

There are described some regularities of variation of sulphur oxide surface concentration under different atmospheric stratification near large power stations with high stacks. Under stable stratifica-

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* Editor's note: The abstract is presented as given in English with the original Russian article.

tion both mean concentrations and their pulsations are not large. Under unstable stratification concentrations pulse with a period of some minutes, and just in these conditions the increase of concentrations exceeding maximum-permissible concentrations (though short-termed) is observed. These maximum concentrations are connected by the author with vertical pulsations of thermal jets. Observations of smoke plumes give valuable information about the atmospheric stability. It is proposed to confirm a single classification of smoke plumes in form of international cloud classification which, according to author's opinion, must take into consideration not only conditions of thermal stability, but wind regime, too.

METHOD OF DETERMINATION OF AVERAGE IMPURITY CONCENTRATION NEAR AN ELECTRIC POWER PLANT BY MEANS OF AN ELECTRONIC COMPUTER

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 31-36, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

When electric power plants are installed, it is necessary to consider the necessity of reducing their harmful influence on adjoining residential areas to a minimum. In solving the given problem, it is not enough to know only the prevailing wind direction. The dispersal of atmospheric pollutants also depends on the frequency of wind velocities and directions, characteristics of the wind profile, and stability conditions.

The problem consisted in allowing mathematically for the complex influence of these meteorological factors on the distribution of impurities by using an electronic computer, and giving a clear representation of the results obtained.

As the chief characteristic of atmospheric pollution we took the mean annual number of hours with a concentration exceeding a given value. The mathematical model earlier proposed by the author [5] consists in the following: the x axis of the Cartesian coordinate system is oriented along the mean wind. Then, in the y and z directions at distance x from the emission source (x, y, 0), the concentrations change according to the Gaussian law, and this change is characterized by the quantity $\sigma_y(x)$ and $\sigma_z(x)$.

We will use the familiar Sutton formula [4], which for concentrations on the underlying surface $z = 0$ is frequently used in the following form:

$$\chi_T(x, y, 0) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}_h} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \exp\left(-\frac{y^2}{2\sigma_y^2}\right). \quad (1)$$

Here χ_T (x, y, 0) is the impurity concentration on the underlying surface; $\bar{u}_h$ is the average wind velocity at the stack height (m/sec); Q is the source output (g/sec); H is the effective source height (m).

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For the wind velocity under the source we use the power law

$$\bar{u}_h = \bar{u}_{h_0}\left(\frac{h}{h_0}\right)^{\gamma}, \tag{2}$$

where h_0 is the height at which the wind velocity is measured, $\bar{u}_{h_0}$ is the wind velocity at level h_0 and γ is an exponent.

The effective source height will be determined from Holland's formula [2]

$$H = h + \frac{V_s d}{\bar{u}_h}\left(1{,}5 + 2{,}68 \cdot 10^{-3} p \frac{\Delta T_d}{T_s}\right) k, \tag{3}$$

where V_s is the exit velocity of the flue gases from the stack orifice (m/sec); d is the stack orifice diameter (m); ΔT_d is the overheating of flue gases (°C); T_s is the absolute temperature of the flue gases (°K); p is the average atmospheric pressure at the stack orifice level (mb); k is a parameter dependent on the stability of the atmosphere.

Substituting (2) and (3) into (1), we obtain

$$\chi_z = \chi_{cent} \exp\left(-\frac{y^2}{2\sigma_y^2}\right), \tag{4}$$

where

$$\chi_{cent} = \frac{Q}{\pi\sigma_y \cdot \sigma_z \cdot \bar{u}_{h_0}\left(\frac{h}{h_0}\right)^{\gamma}} \exp\left\{-\frac{1}{2\sigma_z^2}\left[h + \frac{V_s d}{\bar{u}_{h_0}\left(\frac{h}{h_0}\right)^{\gamma}}\left(1{,}5 + 2{,}68 \cdot 10^{-3}\frac{p\,\Delta T_d}{T_s}\right) k\right]^2\right\}.$$

In these formulas χ_{cent} is the axial concentration, and the second factor in (4) characterizes the concentration distribution in the direction perpendicular to the wind. Direct calculations with formula (4) are made when, for example, it is necessary to evaluate the dependence of the concentrations on the stability of the atmosphere and on the wind velocity and direction near an electric power plant [5].

The statistical distribution of the wind direction usually is not available for the entire 360° range, but only for 16 compass points, so that the frequency of a compass point usually refers to an angular interval of 22.5°. Assuming that within a compass point for the time interval of interest to us the wind directions are distributed evenly, then within this angle, at fixed distances x, the average concentration should be considered independent of y. This concentration χ_T may be determined from the relation

$$\bar{\chi}_{\pi} = \frac{1}{2y_0}\int_{-\infty}^{+\infty} \chi_{cent} e^{-\left(\frac{y^2}{2\sigma_y^2}\right)} dy = \frac{\chi_{cent}\sqrt{2\pi}\,\sigma_y}{2y_0}. \tag{5}$$

Here $2y_0$ is the full width of the current within a compass point at distance x from the source.

It may be approximately assumed that

$$2y_0 = 2x\frac{\pi}{16}. \tag{6}$$

then

$$\bar{\chi}_{\pi} = \frac{16\chi_{cent}\sigma_y}{(2\pi)^{0,5}x}, \tag{7}$$

or

$$\bar{\chi}_{\pi} = \frac{16Q}{\pi^{1,5}\cdot 2^{0,5}\cdot \sigma_z \cdot u_r\left(\frac{h}{h_0}\right)^{\gamma}} \exp\left\{-\frac{1}{2\sigma_z^2}\left[h + \frac{V_s d}{u_r\left(\frac{h}{h_0}\right)^{\gamma}}\left(1{,}5 + 2{,}68\cdot 10^{-3} p\frac{\Delta T_d}{T_s}\right)k\right]^2\right\}, \tag{8}$$

where u_r is a suitably averaged value of the wind velocity u_{h_0}.

Formula (8) may be used for determining the mean hourly concentrations and dependence on industrial factors, on the wind direction and velocity, temperature stratification, and distance to the source.

The effect of meteorological factors, i.e., turbulent diffusion, is taken into account via σ_z, u_r and γ. We determine the given values for each hour of a five-year period on the basis of data of anemometric and radiosonde observations made at the D. M. Marcell Aerological Observatory. This was done in the following manner. The mean vertical lapse rate of the lower 300-meter layer of the atmosphere was determined from data of a daily four-time radiosonde observation. The lapse rates were grouped into seven categories, then subjected to statistical analysis [4]. A catalog of the frequency of stability groups was compiled from temperature stratification data for five years, taking into account the hourly synoptic observations [8]. Combined analysis of hourly data on the atmospheric stability and wind velocity and direction was then performed for h_0 = 10 m.

Table 1 gives some of the results obtained, namely, for a wind velocity interval $\bar{u}_r$ equal to 1.6-3.3 m/sec (average velocity 2.5 m/sec). For the given wind velocity interval, the frequency of stability groups was defined for winds of each of the 16 compass points. In [8], all of the data were published for eight wind velocity intervals (0.1, 0.9, 2.5, 4.4, 6.7, 9.3, 12.3, 16.0 m/sec). The frequency of each of these was also studied.

Table 1

Annual Recurrence of Wind Directions and Velocities and of the Temperature Stratification in Hours.

(Budapest, Aerological Observatory)

Wind Direction	Stability Group							Wind Direction	Stability Group						
	1	2	3	4	5	6	7		1	2	3	4	5	6	7
NNE	25	33	47	45	55	60	9	SSW	3	6	12	12	26	40	11
NE	25	24	33	39	53	66	11	SW	4	8	16	23	44	67	24
ENE	14	18	26	34	51	62	9	WSW	3	6	16	29	41	67	21
E	17	28	41	57	84	106	16	W	5	5	12	23	34	52	14
ESE	18	30	43	52	83	109	19	WNW	1	5	7	16	26	42	9
SE	23	20	36	39	63	100	18	NW	5	7	13	24	42	77	10
SSE	12	12	17	22	29	42	10	NNW	5	10	22	39	64	77	15
S	14	13	19	27	37	60	14	CN	25	30	59	70	104	110	16

Similar treatments were carried out on the wind profile. From data of 11 thousand observations of the vertical wind profile during the same five years, the parameter γ was determined, and a statistical analysis of the dependence of this parameter on the atmospheric stability and wind velocity and direction was performed. The parameter γ was found to display a considerable variability [7]. Table 2 shows results of the dependence of average γ values on the wind direction and atmospheric stability in the same interval of wind velocities as in Table 1.

Table 2

Dependence of Parameter on the Wind Direction and Velocity and Also on the Temperature Stratification.

Wind Direction	Stability Group						
	1	2	3	4	5	6	7
NNE	0,16	0,18	0,20	0,20	0,17	0,16	0,07
NE	0,20	0,23	0,24	0,17	0,20	0,17	0,10
ENE	0,24	0,25	0,28	0,26	0,23	0,17	0,15
E	0,19	0,26	0,32	0,26	0,25	0,18	0,18
ESE	0,27	0,27	0,32	0,28	0,25	0,19	0,17
SE	0,32	0,34	0,34	0,32	0,24	0,21	0,17
SSE	0,33	0,33	0,33	0,30	0,23	0,25	0,17
S	0,31	0,30	0,30	0,30	0,21	0,21	0,16
SSW	0,30	0,29	0,26	0,26	0,21	0,19	0,14
SW	0,30	0,31	0,27	0,24	0,20	0,17	0,13
WSW	0,30	0,31	0,29	0,26	0,18	0,16	0,12
W	0,37	0,27	0,30	0,23	0,20	0,14	0,09
WNW	0,39	0,20	0,34	0,22	0,25	0,19	0,08
NW	0,25	0,20	0,26	0,22	0,20	0,15	0,08
NNW	0,12	0,17	0,19	0,22	0,18	0,14	0,09
N	0,14	0,17	0,19	0,22	0,18	0,16	0,08

In the works of Crammer [1] and Pasquill [3] published earlier, the experimental data were used to find the dependence of the dispersion σ_z on the atmospheric stability and distance to the source. In these studies, the stability was considered only indirectly by using data on the cloudiness and wind at different hours of the day. We also used the Crammer-Pasquill dependence of σ_z on the atmospheric stability, but this dependence was determined directly from the mean lapse rate of the lower 300 meter layer of the atmosphere.

As a practical application of the method proposed, we carried out calculations for the sulfur dioxide concentration in connection with the expansion of a steam power plant located in the area of Százhalombatta (Hungary). Here, at a distance of 26 m to the NNW from the existing stack, a second stack was to be constructed.

Given below are the emission parameters of the electric power plant, subscripts 1 and 2 indicating the parameters of the existing and projected stacks respectively: $h_1 = h_2 = 200$ m, $Q_1 = 2680$ g/sec, $Q_2 = 3320$ g/sec, $V_{s_1} = 14.5$ m/sec, $V_{s_2} = 18.0$ m/sec, $d_1 = d_2 = 9$ m, $T_{s_1} = T_{s_2} = 418°K$, $\Delta T_1 = \Delta T_2 = 136°C$, $p = 974$ mb, $k = 0.8-1.2$.

To determine the average concentrations, the sources were reduced to a single point, and the concentration was determined as the sum of the concentrations from the individual stacks. The calculations were made on a computer for the following distances: 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.0, 10.0, 20.0, 50.0, and 100.0 km. The average frequency of stability groups and wind velocities and directions was taken into account.

The number of hours per year when the surface concentration of sulfur dioxide ranged from 0.25 to 0.75, 0.75 to 1.00, and above 1 mg/m^3 was calculated. The zones of maximum frequency of high concentrations were found to be located to the WNW and SSE from the electric power plant at distances of 1.5-7 km from the stacks. The maximum concentrations were noted at distances of 1.0-1.5 km.

After the electric power plant is expanded, it is proposed that the results of the calculations be checked by conducting field observations.

The proposed method should be used where systematic aerological observations have been carried out in the vicinity for at least a year. Under level conditions, the distance to the points at which the observations are made can be up to 150 km.

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D. SZEPESI

THE ESTIMATION OF MEAN POLLUTANT CONCENTRATION NEAR POWER STATIONS WITH THE HELP OF ELECTRONIC COMPUTER*

While calculating air pollution by power stations, frequency of different meteorological factors is taken into account in order to minimize their harmful effect on population. The calculations are carried out on Sutton's formula and effective source height is found on Holland's formula. By averaging concentrations in the range of one point, calculation formula is brought to the form suitable for employment of annual mean wind rose at the calculations of annual mean air pollution characteristics.

Complex characteristic of frequency and interconnection of atmosphere stability and all necessary for calculation wind characteristics are given for 5 years on the basis of statistical treatment of observation data of Aerological Observatory after D. Marcell. Along with these data, vertical diffusion parameter σ_z is used at calculations which is determined on Crammer-Pasquill graphs on the base of actual data of mean lapse rate in the lower 300m air layer.

Annual mean number of hours with concentration surpassing the given value is used as a main characteristic of air pollution.

A brief description of calculations for a power station is given.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

METHODS OF CALCULATION OF THE SURFACE CONCENTRATION OF A GASEOUS IMPURITY DISCHARGED FROM AN ELEVATED SOURCE

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 37-43, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

1. Maximum Surface Concentration and Some Formulas Used for its Calculation

The intensity of pollution of the atmospheric surface layer with an impurity discharged from an elevated source is chiefly characterized by the maximum concentration that can be expected near the source. In order to calculate or determine this maximum, various formulas have been derived in several countries which express its dependence on the conditions of emission of the impurity and on the dispersion.

In Great Britain, Sutton proposed the formula

$$C_m = \frac{2Q_p \cdot 10^3}{\pi e u h^2} \frac{C_z}{C_y} \ (\text{мг/м}^3). \tag{1}$$

where Q_p is the ejection velocity of the gaseous impurity or aerosol from a continuous source (g/sec), u is the mean wind velocity at the stack orifice level (m/sec), h is the effective source height, and C_y and C_z are coefficients characterizing turbulent diffusion in the transverse and vertical directions y and z respectively. These coefficients depend on the vertical thermal stratification of the atmosphere. It follows from formula (1) that the maximum surface concentration is directly proportional to the amount of discharged impurity and inversely proportional to the wind velocity and square of the effective stack height.

In 1962 in the Federal Republic of Germany, on the basis of a solution of the diffusion equation in a more general form, proposed by Pasquill and modified by Wipperman and Klug, the following formula was obtained:

$$C_m = \frac{Q_p (2r)^r \cdot 10^3}{\pi e^r u h^{2r}} \frac{G \frac{f}{g}}{F} \ (\text{мг/м}^3), \tag{2}$$

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* Editor's note: Certain inconsistencies between the transliteration of Russian phonetic spelling of non-Russian names and the accepted spelling of these names is unavoidable. For purposes of bibliographical referencing, the transliterated phonetic spelling is given first and the non-Russian spelling is given parenthetically.

where $r = \frac{f + g}{2g}$. The values of the parameters F, G, f, and g were obtained from results of American experimental field studies.

In 1963, in the Soviet Union, a formula was derived that was obtained from theoretical and experimental studies directed by M. Ye. Berlyand. For gaseous impurities, it has the following form:

$$C_m = \frac{AQ_p m}{H^2 \sqrt[3]{V_1 \Delta T}} \ (\text{мг/м}^3). \tag{3}$$

where A is a coefficient dependent on the thermal stratification of the atmosphere and wind velocity ($\sec^{2/3} \deg^{1/3}$), H is the effective stack height (m), V_1 is the volume of gases discharged from the stack (m^3/sec), ΔT is the temperature difference between the flue gases and the surrounding air (°C), and m is a dimensionless coefficient related to the discharge velocity of the gas.

In the formulas cited above, a single stack distant from the other pollution sources is considered. The grounds around the stack are assumed to be flat and without buildings.

In the last few years, many countries have undertaken numerous studies in order to find a relationship between the parameters of the working formulas characterizing the conditions of turbulent diffusion and thermal stratification of the atmosphere, fluctuations of the wind direction and velocity, source height above ground, and sampling time.

In calculations with formulas (1) and (2), and also in the derivation of formula (3), use is made of various formulas for determining the effective ascent of the plume above the stack orifice. Analysis of the various methods of calculation of this quantity is given in Bem's (Bohm's) paper (see this collection).

Results of calculations based on these formulas differ appreciably from one another. It appears desirable, therefore, to organize an international collaboration among specialists working in this area.

2. Experimental Studies Conducted in Czechoslovakia

In Czechoslovakia, the problem of calculating the air pollution produced by electric power plants operating on brown coal is one of major importance. The one-time MPC of sulfur dioxide in Czechoslovakia is the same as in the USSR (0.5 mg/m^3). It refers to a half-hour period of sampling. The above methods of calculation were studied with reference to the given problem. This was done by conducting comparatively short-term field experiments on the dispersal of sulfur dioxide discharged from stacks of steam power plants.

In 1964 and 1965, three surveys were carried out in the vicinity of two electric power plants, each survey lasting two weeks. Specialists in power engineering, hygiene, and meteorology participated in the studies. The first electric power plant (hereinafter denoted by the index "1"), with a capacity of 300 MW, was located in a valley and had two stacks 120 m high; the second plant (index "2"), with a capacity of 600 MW and a single stack 200 m high, was located at the foot of a mountain chain rising 500 m above the base of the stack at a distance of 15 km. Four groups of quantities were studied: emission parameters, ascent of smoke plume, meteorological parameters, and distribution of the surface concentration of sulfur dioxide. We will give a brief description of these experiments along with an analysis of the results and recommendations for their use.

The emission parameters were measured only in the daytime, usually in the course of 8-10 hours. Characteristic samples of coal were taken for the analysis, as well as samples of slag and ash. The loads on the individual power units and the coal consumption were also recorded. Simultaneously, samples of the flue gases were taken and their temperature measured. This made it possible to calculate the emission of sulfur dioxide as approximate information. Considering the presence of short-term fluctuations in the emission of sulfur dioxide, measurements of sulfur dioxide concentrations in the flue gases were also made by means of gas analyzers. The volume of the flue gases discharged was also calculated.

The plumes were photographed with cameras located at a certain distance and operating at right angles to the direction of the plumes. In studies at power plant 1, a photogrammetric method was used, and at power plant 2, only one camera was employed. The characteristic value of the plume ascent used was the average of three photographs taken at 10-second intervals. Since the plume was followed on the photograph only to distances of about 400 m from the stack, its final rise was determined by extrapolation.

The instruments for measuring the wind velocity and direction in the first case were located between two stacks at a height of about 90 m. In the second case, a steel mast 80 m high was set up on a hill at a distance of 1.2 km from the stack; its top was located at the midpoint level of the stack. The stability of the atmosphere was determined primarily on the basis of general meteorological observations, since the use of the large captive balloon available was restricted by the fact that most of the time the wind velocity exceeded the limits allowed for its ascent.

Measurements of the surface concentration of sulfur dioxide were based on the Best-Gaeke calorimetric method and on a photometric treatment of the samples. The instrument for collecting the field samples was battery-operated. In the first case, 30 such instruments were used, and in the second case, 40. The sampling time was 30 minutes. At the end of each sampling period, the operators poured the absorber into a glass test tube and refilled the bubbler with fresh absorbent. The sampling was conducted daily for 6-8 hours. The samples were processed in the laboratories of the power plants.

The measurement data were plotted on a graph and distributed over arcs of sectors of circles whose center was located at the base of the stack, and the axis was directed along the wind. The radii were 1.5, 2.5 and 4 km for the first power plant and 3, 5.5, 9 and 13 km for the second. The angular distances of the points of measurement ranged from 5 to 10°.

Every morning, depending on the weather forecast (the weather forecasting group also took part in the expedition), the sampling instruments and the operators were brought to the points of measurement, located on the lee side of the stack at the above-indicated distances.

The observed values of the discharge velocity, plume ascent and wind velocity were initially represented in the form of time graphs. The surface concentrations were then compared with the amount of emissions, plume ascent and wind velocity.

For purposes of further analysis, consideration was given to the results of only those sampling periods for which the maximum concentration and also the wind velocity and plume ascent could be reliably established. The discharge velocity of sulfur dioxide changed slowly from one hour to the next. Of the large number of measurements, values of all the parameters were obtained for 21 experiments in the area of the first facility and for 23 experiments in the area of the second. A neutral or moderately unstable stratification prevailed in both expeditions. In the presence of stable stratification, there were only a few observations, which are not considered here. The observed values of the field maximum ranged from 0.15 to 0.65 mg/m^3, the wind velocities from 4 to 14 m/sec, and the amount of sulfur dioxide discharged ranged from 1.4 to 2.4 kg/sec (power plant 1) and from 4.3 to 6.3 kg/sec (power plant 2).

3. Analysis of Data

The observed values of the field maxima were compared with those calculated with Sutton's formula (1). This was done by considering only the highest theoretical value of the maximum, which may be encountered in the presence of isotropic dispersion during a short period of sampling, i.e., when the ratio C_z/C_y is equal to unity. Such a maximum, which may be termed "isotropic", is equal to

$$C_{is} = \frac{235Q_p}{uh^2}. \qquad (3a)$$

For each sampling period, this isotropic maximum was calculated from the observed values of the parameters Q_p, u, h and was then compared with the observed 30-minute field maximum, which may be denoted by C_{m30}. Their ratio $\alpha_{30} = C_{m30}/C_{is}$ characterizes the diffusion anisotropy, influence of sampling time and other factors. The values of the ratio range from 0.07 to 0.45, and the distribution of the frequency of the values of this ratio for the first and second facility are very similar; their respective averages were 0.21 and 0.23, and the standard deviations, 0.10 and 0.11.

A check of the significance of the differences between the dispersions and averages made by using the Fisher and Student criteria, showed that they were statistically insignificant, so that all 44 results in both groups could be regarded as belonging to a statistically homogeneous set.

Fulfillment of the Kolmogorov-Smirnov criterion showed that this distribution of the concentration frequency may be regarded as normal. It becomes possible to determine the parameters of a hypothetical normal set, parameters that would be obtained from a large number of similar measurements. From the average of our 44 values (0.22) and their standard deviation (0.10) it was found that with a probability of 90%, the expected mean value would lie in the range from 0.19 to 0.25, and the standard deviation, in the range 0.09-0.12.

The theoretical isotropic maximum obtained from Sutton's formula must be multiplied by a_{30} in order to obtain the half-hourly maximum occurring around the source under given conditions of emission and diffusion. This coefficient changes from 0 to 1, i.e., the half-hourly field maximum may reach values from 0 to the theoretical isotropic maximum. These differences are related to fluctuations of the parameters of turbulent diffusion and observation errors.

To forecast the 30-minute maximum, one must select a given value of the coefficient a_{30}. Further, one can determine the probability with which the predicted maximum will be exceeded. We take the normal distribution of the frequency of a_{30} values with a mean M = 0.25, located at the upper limit of the expected values, and a standard deviation s = 0.10. If we choose a_{30} = 0.4, it will differ from the mean by 0.40-0.25 = 0.15, i.e., by 0.15/0.10 = 1.50s. The area under the curve of normal frequency distribution from the mean to 1.50s will be $\Phi(1.50) = 0.433$, so that the probability that this value will be exceeded is 0.5-0.433 = 0.067. The predicted field maximum

$$C_m = 0.4 \cdot 235 Q_p/uh^2$$

will probably be exceeded in the course of 6.7% of the time, during which the conditions of pollution of the surface layer of the atmosphere are characterized by the parameters Q_p, u, h and a neutral or slightly unstable thermal stratification.

4. Use of the Measurement Results

Results of the above-mentioned field studies were also used to obtain data for determining the plume ascent. Simultaneously with observations of the plume ascent and wind velocity, the rate of thermal discharge from the sources Q_t (MW) and the discharge velocity were determined. The agreement of the different formulas for calculating the plume ascent was studied. The comparison made by Bem (Bohm) showed a good agreement with the Lucas-Moore-Spurr formula.

$$\Delta h = \alpha \frac{Q_t^{1/4}}{u} \ (\text{м}). \tag{4}$$

On the average, the plume ascent coefficient α was found to be equal to 130 in the case of power plant 1 (120 m stack) and 250 in the case of power plant 2 (200 m stack).

These results were also used to work out a method for calculating the pollution of the surface layer of the atmosphere that could be expected from large steam power plants. Under the direction of the "State Technology Committee", this method was prepared by a group of experts.

Limitations apply primarily to the maximum concentration in the presence of the so-called dangerous wind velocity, when the surface concentration is greatest. At such a velocity, as follows from formulas (3a) and (4), the plume ascent is equal to the stack height (Δh = H), so that the plume height above ground level will be h = 2H. The dangerous wind velocity is

$$u_{crit} = \frac{\alpha Q_t^{1/4}}{H}. \tag{4a}$$

The concentration maximum under isotropic conditions is determined from the following formula:

$$C_{is} = \frac{235 Q_p}{4\alpha Q^{1/4} \cdot H} \ (\text{мг/м}^3). \tag{5}$$

The coefficient α in the formulas can first be determined by interpolation or extrapolation of the values obtained by Bem (Bohm).

To predict the 30-minute maximum, the coefficient $a_{30} = 0.4$ was chosen. In conformity with (5), the predicted maximum for a neutral stratification will be

$$C_{m_{30}} = \frac{23{,}5 Q_p}{\alpha Q_t^{1/4} \cdot H} \ (\text{мг/м}^3). \tag{6}$$

This formula should be regarded as preliminary. Its refinement will require further investigations.

L. NĚMEC

A CONTRIBUTION TO THE METHOD OF CALCULATING THE GROUND LEVEL CONCENTRATION OF GASEOUS POLLUTANT EMITTED FROM AN ELEVATED SOURCE*

In Czechoslovakia the problem of air pollution by sulphur dioxide caused by power stations burning brown coal is quite important. In this connection, experimental observations of air pollution in the vicinity of two power stations have been carried out recently with simultaneous investigation of emission parameters, plume rise and meteorological factors. One of these power stations is situated in a plain and is equipped with two chimneys 120m high; the other one, with one chimney 200m high, is situated on the foot of a mountain chain. The paper contains a short description of these experiments with an analysis of their results and the way of their application. The interpretation of obtained results was carried out by comparison of measured maximum concentrations with those computed on the base of Sutton's equation, and the effective source height was determined with the help of the formula proposed by Lucas, Moore and Spurr. On the base of comparison of computed and experimental data some average parameter values of these formulas representative for the conditions in Czechoslovakia were established. This allowed to prepare air pollution calculating method for large power stations.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

RESULTS OF EXPERIMENTAL STUDY OF SMOKE PLUMES
. FROM THERMAL POWER PLANTS

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 44-48, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The model for calculating atmospheric pollution in the area of a source of combustion products essentially consists of two separate parts. First of all, it is necessary to determine the initial height to which the combustion products rise. Then, it is necessary to determine the concentrations of the noxious gases. In the second phase they may be assumed to be present in the atmosphere as passive impurities, i.e., to spread only under the influence of the wind and turbulent diffusion. In the present study, we shall dwell on the first of the indicated stages, i.e., on the ascent of the smoke plume under the influence of a higher temperature and entrainment velocity.

In 1959 in Czechoslovakia, at the initiative of power engineers, a small group was formed that specialized in the problem of dissemination of combustion products from plant stacks. Even our first expeditionary studies showed that the generally accepted models for the height of smoke ascent contradicted our tentative experimental data. The models frequently recommended for calculating the height of ascent, such as the formulas of Holland or Bosanquet, when applied to large-capacity heat sources (100-200 MW), gave results that disagreed with the experiment. Therefore, in 1962 we began studies of the ascent of smoke plumes from large electric power plants. In particular, it was decided to check the dependence of the height of the plume axis on the thermal capacity of the source and on the wind velocity, and also to determine which of the known models for the ascent height can be used in design calculations for large electric power plants.

The experimental observation of smoke plumes was carried out in the framework of expeditionary studies in the area of the thermal power plants of Opatovice and Tusimice in 1963 and 1964. These expeditionary measurements involved the determination (with a fair degree of reliability) of the parameters of combustion products and of the wind velocity and direction at the height of the stack orifice. Thus, it was possible to supplement the indicated expeditionary observations and processed results of these experiments.

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* Editor's note: Certain inconsistencies between the transliteration of Russian phonetic spelling of non-Russian names and the accepted spelling of these names is unavoidable. For purposes of bibliographical referencing, the transliterated phonetic spelling is given first and the non-Russian spelling is given parenthetically.

We carried out the observations of the smoke plume by using a simple photogrammetric method that had been used, for example, in the U.S.A. by Moses and Strom for a small experimental stack. The smoke plume was photographed from two locations on either side of the plume. The results were processed in such a way that on the optical bench, the photographic negatives were projected on a plate rotating around a mockup of the stack. Thus, the method employed is substantially cheaper than the use of phototheodolites and, on the other hand, considerably more accurate than photographing from one location, which may give rise to appreciable errors in case of an imperfect determination of the direction of the plume or in case of its deflection. To take the photographs, we used unmodified cameras with a frame size of 24 x 36 mm and a focal length of 50 mm. The cameras were firmly mounted on specially adapted tripods that make it impossible to adjust the direction of the camera axis accurately.

Initially, we used black-and-white material of 10 DIN, and later switched to reversible color film. Each individual measurement made in a given period consisted in each separate case of ten shots at one-minute intervals. Their analysis involved the use of the corresponding 10-minute average values of the wind velocity and other meteorological parameters.

An evaluation showed that in most cases, out of 10 shots, one can determine the time-averaged axis height above the stack orifice with an accuracy above 10%.

A total of 76 measurements were made, including 59 that pertained to the power plant in Opatovice, and 17 to the power plant in Tusimice. The installed capacity per stack of the power plant in Opatovice was 155 MW. In Tusimice, it amounted to 400 MW, but the actual capacity was mostly around 200 MW. The thermal capacity of the source in the former case was about 60 MW, and in the latter case it sometimes reached 100 MW. The height of the Opatovice stacks was 120 m, and that of the Tusimice stack, 195 m. The power plant in Opatovice was located on a nearly perfect plain, whereas at a distance of 20 km from the Tusimice power plant were the Rudnye Mountains.

In processing the results obtained, the height of the plume axis was determined in each individual case at distances of 25, 50, 75, 100, 150, 200, 250, 300 and 400 m from the stack. At large distances, the plume axis could be determined only in rare isolated cases. In many cases it was possible to determine the plume height only at a distance of 150-200 m.

The results were processed in three stages. First, the geometric parameters of the location of the plume were evaluated empirically. The data obtained were then compared with results of calculations using known formulas. This also served to check their applicability to plumes from large-capacity sources. Finally, the calculation made with the formulas we are proposing were compared with the results of foreign studies.

The measurements performed showed that at a wind velocity above 3 m/sec, the height of the plume axis is approximately determined by means of a power function of the distance from the stack. Then the exponent of such a function is 0.57 and is independent of the wind velocity. Obviously, this relation is approximately valid for distances not exceeding 400 m. For greater distances, it is inapplicable for completely understandable physical reasons. Using known theoretical arguments on the dependence of the initial ascent on the thermal capacity, as indicated for example in the studies of Priestley and Spurr, on the basis of our experiments we can write that

$$h = 7{,}34Q^{1/4}x^{0{,}57}u^{-1{,}15}. \qquad (1)$$

where h is the axis height (m), Q is the thermal capacity (MW), x is the distance from the source (m), and u is the wind velocity (m/sec).

As already stated, this relation remains in force at a distance up to 300-400 m from the source and at a wind velocity of at least 3 m/sec. At lower wind velocities, the smoke plume of the power plant rises much more steeply.

We also established the empirical relations for the so-called ascent height of the plume. The measured ascent height was determined in two ways. First, by ascent height was meant the height of the plume axis at the small distance at which it was estimated from the measurement data. This was close to Priestley's concept, according to which the total ascent is equal to the height of the plume axis at a sufficiently large distance from the source. In this case, the ascent height will be

$$\Delta h = 151Q^{1/4}u^{-1{,}08}. \qquad (2)$$

We also obtained a formula for the ascent height by taking this quantity to mean, according to Sutton, the height of the plume axis at a distance where it makes a sufficiently small angle with the horizontal. In the given case, the angle was 10°. The ascent height Δh^{+} determined in this manner is directly proportional to the thermal capacity of the source, and from our experiments it follows that

$$\Delta h^{+} = 43Qu^{-2{,}67}. \qquad (3)$$

It was also checked to what extent our measurement results corresponded to known formulas for the ascent of smoke plumes, and hence, to what extent these models were applicable to plumes from sources of relatively high capacity.

The analysis involved the use of the formulas of Braydnt*-Davidson (1949), Sutton (1950), Bosanquet, Carey* and Gelton* (1950), Holland (1953), Thomas (1954), Morton, Taylor and Turner (1956), Priestley (1957), Bosanquet (1957), Chenedi* (1956), Sutton-Best (1957), Scorer (1959), Shtyumke* I and II (1961), Lucas, Moore and Spurr (1963), Berlyand (1963), Raukh* (1964), and Danovich and Zaygel' (1964). In all cases, the concepts of the formulas' authors were taken into account, in particular, with regard to the values of the constants contained in the formulas. In principle, conditions of neutral stratification were postulated. We determined the correction factor for all the formulas (regardless of whether we were dealing with the ascent height or plume axis height as functions of the distance from the stack). We also checked whether the formula correctly reflected the dependence on the wind velocity.

From the results obtained it follows that the height of the plume axis at various distances from the stack may be satisfactorily determined by means of the Priestley relation. The total ascent of the plume is adequately determined by the Priestley-Spurr, Berlyand, and Danovich-Zaygel' formulas. Since the question of interest is that of the use of projected sources of even greater capacity, in keeping with the prevailing concept of the ascent height, one can expect an acceptable agreement when the indicated relations or the empirical formula we derived is used.

We also checked to see whether our empirical relations were in agreement with results of observations of smoke plumes from sources of different capacities for the purpose of studying the possibility of applying them to the case of large capacity sources. A comparison could be made by taking only those data of foreign studies that gave the values of all the necessary parameters. We found our model for the ascent height Δh to be in good agreement with the results of the foreign experiments. This was also the case for sources whose thermal capacity was much lower than in our experiments (for example, in the studies by Moses and Strom).

At the present time, it is proposed that the procedure for calculating air pollution should include an expression for the ascent height, according to which the latter is proportional to the fourth root of the caloric power. In accordance with the results of American experiments and certain theoretical considerations, it is proposed that the procedure should include the assumption that the "proportionality constant" increases with the stack height. The results obtained also indicate as much, but thus far there is no basis for considering this assumption proven.

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* Transliteration of Russian spelling

B. BOHM

RESULTS OF EXPERIMENTAL INVESTIGATION OF POWER STATION PLUMES*

In the paper data analysis of investigation of plume rise from power stations situated in Opatovitze and Tushimitze is given. The source height in Opatovitze amounts to 120m and has thermal output of 100MW, and the source situated in Tushimitze has the height of about 195m and thermal output about 60MW.

Experimental works on determination of plume rise height were fulfilled in the period of 1963—64. Observations of stack plumes were carried out with the help of two cameras having $f = 50$mm and frame of 24×36mm. Cameras were situated on special tripod which gave the opportunity to determine the direction of main optical axis of cameras. The treatment of results was carried out by projecting negatives on the plate rotating around stack model. Black-white negative film FF was used as a photograph material and colour reversal film was employed at the end of the test. Emission parameters and wind velocity and direction at the stack top height were determined simultaneously with photographing of stack plumes.

The plume axis height was determined in each measurement at the distance of 25, 50, 75, 100, 150, 200, 250, 300 and 400m from the source. From data analysis it was found that the plume axis height can be described by the formula: $h = 7.34Q' \cdot x^{0.57} u^{-1.5}$ where h is plume axis height in m, Q is thermal output in MW, x is the distance from the source in m, u is wind velocity in m/sec. This ratio is valid up to distances of 300—400 m at wind velocity > 3 m/sec. Data comparison is carried out on the basis of well-known formulas for plume rise met in literature. From obtained results one can draw a conclusion that the plume axis height is in good accordance with Priestley equation.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

ATMOSPHERIC DIFFUSION AND STRUCTURE OF THE AIR FLOW ABOVE A NONUNIFORM UNDERLYING SURFACE

M. Ye. Berlyand and Ye. L. Genikhovich (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 49-69, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

Results of the modern theory of turbulent diffusion pertain for the most part to conditions of a featureless and horizontally uniform underlying surface. For these conditions, the basic relationships have been studied, working formulas have been derived, and practical recommendations have been made.

The problems of the dissemination of an impurity over a nonuniform underlying surface have been studied very little. Moreover, industrial enterprises discharging noxious substances and residential centers are frequently located on rugged terrain with an appreciable height difference, near water reservoirs, etc. It is therefore of scientific and practical importance to evaluate the effects caused by the nonuniformity of the land surface, to study the scope of applicability of results of the study of turbulent diffusion which have been obtained for horizontally uniform conditions, etc.

This study will examine two types of nonuniformities of the underlying surface. One pertains to surface irregularities of a given area characteristic of a hilly terrain. The other is related to the presence of temperature contrasts arising, for example, at the boundary of water reservoirs.

In a theoretical study of the processes of atmospheric diffusion for such conditions and their comparison with the transport of an impurity over a homogeneous surface, in the first case one can discuss the effect of a dynamic disturbance, and in the second case, a thermal disturbance of the boundary. In both cases, the dissemination of the impurity in the atmosphere is described by the equation

$$u \frac{\partial q}{\partial x} + w \frac{\partial q}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial q}{\partial z} + k_y \frac{\partial^2 q}{\partial y^2}. \qquad (1)$$

Here q is the impurity concentration, u and w are the horizontal and vertical components of the velocity of air, and k_z and k_y are the vertical and horizontal components of the turbulent exchange coefficient. The x axis is oriented parallel to the wind, the y axis, perpendicular to it in the horizontal plane, and the z axis, along the vertical.

As boundary conditions, as in the case of a homogeneous terrain, it is assumed that the impurity flow is nil on the underlying surface in the case of dry land, and in the case of a water reservoir, the impurity concentration at an infinite distance from the source must decrease to zero. The initial conditions assume the presence of an impurity source. The coefficients of equation (1) in the cases considered are complex functions of the coordinates, and its integration can be carried out in practice only by numerical means. To do so, one can make partial use of already developed methods for numerically solving the problem of dissemination of an impurity over a featureless terrain [2, 3].

In order to simplify the problem, the underlying surface will be assumed uniform in the direction perpendicular to the mean wind. This makes it possible to relate the impurity concentrations from a point source and a linear source by using the relation $k_y = k_0 u$ [1], as was done for a uniform underlying surface. Thus, further discussion can be confined to the case of a linear source.

The results obtained in [2] and [3] make it possible to integrate expression (1) numerically for a given type of functions expressing the dependence of u, w and k_z on the coordinates. Unfortunately, these dependences practically have not been studied for the indicated conditions. Therefore, the calculation of the dynamic and thermal disturbances of the boundary and of the associated change in the structure of the air flow consists primarily in evaluating the changes of the coefficients contained in (1). In this formulation of the problem, the determination of the impurity concentration field and structure of the air flow should be carried out simultaneously.

Structure of the Air Flow and Atmospheric Diffusion Under Hilly Terrain Conditions

The character of impurity dispersal under rugged terrain conditions can be studied in various ways. A comparatively simple method consists in using interpolation models for the wind velocity and exchange coefficient [4, 5]. The basis for the construction of these models are certain results of microclimatic observations [6, 11] from which relations are established between the wind velocity values at a fixed level in the surface air layer (usually at height z = 1 m and z = 2 m) in different parts of a hilly terrain. The relations obtained include the increase in wind velocity on windward slopes and the possibility of attenuating it on leeward slopes. There are practically no analogous observational results for higher levels. However, it is known that the vertical wind profile in the surface layer does not differ much from a logarithmic profile. This makes it possible to construct an approximate model of the change in wind velocity with height for a hilly terrain [4, 5]. The simplest approximation can also be proposed for the exchange coefficient by postulating that it changes in proportion to the wind velocity. The vertical component of the air velocity is found from the continuity equation.

On the basis of such a scheme, the integration of expression (1) was carried out, and calculations were made for a number of characteristic instances of a hilly terrain. Some results of the calculation are illustrated in Fig. 1. The latter gives curves of the change of s, proportional to the concentration discharged from a source with height H = 150 m, as a function of x. The same figure shows the profile of the hill studied, with a height of 100 m and a horizontal extent of 1000 m. Curves 1-4 pertain to different locations of the source on the hill, and curve 5, to the location of the source on featureless terrain.

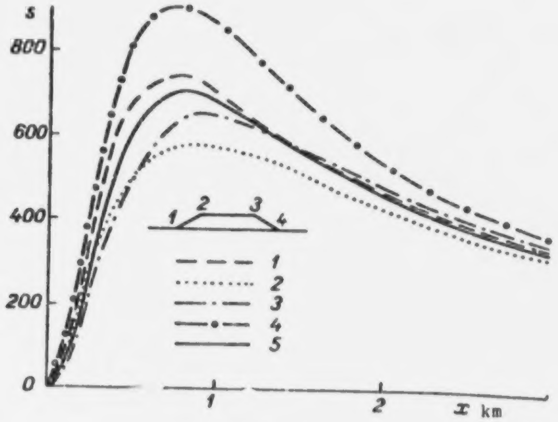

Fig. 1.

From the calculations performed it follows that the difference between the maximum values of the concentrations at different locations of the source on a terrain with a 50-100 m difference in levels and a 5-10° angle of the slopes amounts to 30-50% for source heights of 50 to 200 m. This difference decreases with increasing height of discharge of the impurity.

Another approximate method of studying atmospheric diffusion above a hilly terrain involves the plotting of potential flows of a nonviscous fluid. It consists in plotting the velocity field of an air current by means of conformal mapping of the region of flow on a half-plane. The tolerable error in the description of the structure of the current decreases with increasing distance from the underlying surface, since the influence of viscosity is manifested chiefly in a relatively thin layer near the lower boundary. The results obtained are consequently more applicable to comparatively high sources.

The method under consideration is convenient in that it permits a direct evaluation of the correction to the height of smokestacks which is due to the influence of the topography. In addition, it is possible to omit the complex stage of calculation of the impurity concentration. Such a method has been used in the last few years by Shtyumke [12, 13]*. However, the latter confined himself to analyzing the equation of turbulent diffusion with constant coefficients. Moreover, he used conformal mapping with discontinuous boundary values of the derivatives. As a result, for certain important cases, he obtained impurity concentration values that were infinitely larger, which of course does not correspond to reality.

To plot the potential flow in a region with a curvilinear boundary, one introduces an analytical function of the complex argument t = x + iz, this function being usually referred to as the complex potential:

$$\tau(t) = \varphi(x, z) + i\psi(x, z)$$

from complex argument t = x + iz. It is plotted so that the point (ϕ, ψ) in plane τ moves along the real axis when the point (x, z) moves in plane t along the boundary of the region of flow. The horizontal and vertical components of the velocity of the potential flow are then expressed by the formulas

$$u_n = \frac{\partial \varphi}{\partial x} = \frac{\partial \psi}{\partial z}; \quad w_n = \frac{\partial \varphi}{\partial z} = -\frac{\partial \psi}{\partial x}.$$

The curve ψ (x, z) = const is the flow streamline; in particular, the zero streamline [ψ(x, z) = 0] is the boundary of the region.

Let us now consider the flow coordinates ϕ and ψ (they are sometimes called Boussinesq variables). If they are substituted into the equation of turbulent diffusion of the velocity of potential flow, and the terms describing the impurity exchange along the flow are neglected, the equation for a linear source will assume the form

$$\frac{\partial q}{\partial \varphi} = \frac{\partial}{\partial \psi} k \frac{\partial q}{\partial \psi}. \qquad (2)$$

Correspondingly, the initial and boundary conditions will be transformed as follows:

$$\text{for } \varphi = \varphi_H \quad q = Q\delta(\psi - \psi_H);$$
$$\text{for } \psi = 0, \quad k\frac{\partial q}{\partial \psi} = 0;$$
$$\text{for } \psi \to \infty \quad q \to 0. \qquad (3)$$

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[*] References missing from bibliography [transl.].

Here θ is the capacity of a source located at point $x = x_H$, $z = H + h(x)$ in Cartesian coordinates or at point (ϕ_H, ψ_H) - in flow variables. The lower boundary $\psi = 0$ corresponds to the level of the underlying surface $z = h(x)$.

We set $k = k(\psi)$, which is a natural generalization of the dependences usually employed for the exchange coefficient. Then it is easy to see that the diffusion process is described in Boussinesq variables by the same equations as in Cartesian coordinates for conditions of a horizontally uniform terrain. It follows that in cases where the sources are located on one and the same streamline, the surface concentration maxima have the same values. This conclusion, obtained for linear sources, can be approximately extended to the case of point sources.

The results obtained lead directly to certain practical recommendations. Indeed, the minimum level of the source or the stack height corresponding to it is usually determined from the condition that the maximum of the surface concentration is less than the maximum permissible value (MPC). We will assume that for a horizontally uniform terrain, the height of this level is equal to H_0. For a curvilinear boundary of the underlying surface, the corresponding condition will be fulfilled if the source is located on a streamline that in the incoming flow is located at a distance H_0 from the lower boundary. The height of the source for $\phi=\phi_H$ is determined by the distance $z(\phi_H, \psi_{H_0})$ from the streamline $\psi=\psi_{H_0}$ to the level of the underlying surface $z = (\phi_H, 0)$. Accordingly, the correction factor r to the height H_0 is determined from the relation

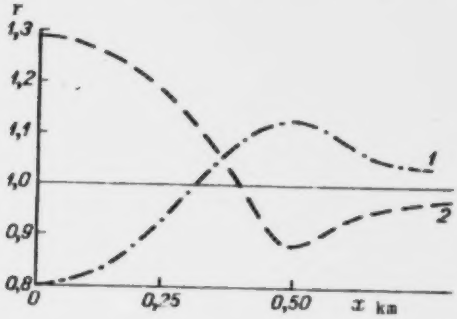

Fig. 2.

$$r = \frac{1}{H_0}\left[z(\varphi_H, \psi_{H_0}) - z(\varphi_H, 0)\right]. \tag{4}$$

Figure 2 gives values of r for a hill (1) and a depression (2) with a 100 m height difference and an extent of 1000 m. Corrections to the concentration maximum in this example are as high as 30-50%. It is characteristic that they are close in magnitude to the corrections obtained on the basis of interpolation models.

The comparative simplicity and clarity of the method discussed permits its use for the evaluation of the influence of certain topographic forms. However, its use is restricted by the fact that it gives a distortion of the field of flow velocities near the underlying surface, a symmetric pattern in the flow distribution on the windward and leeward slopes, etc. It is therefore necessary to switch to more complete schemes.

Let us note that A. A. Dorodnitsyn, I. A. Kibel', L. N. Gutman, and others have already conducted a number of major investigations pertaining to the hydrodynamics of flows caused by orography. For the most part, they pertain to large-scale motions, when the influence of the turbulence of the surface air layer can be excluded. However, an important part in the dispersal of industrial emissions, allowing for the influence of the topography, is played by turbulent exchange processes, which substantially complicates such studies.

The problem can be simplified by using methods of the theory of the boundary layer of a viscous fluid. In addition, in order to reduce the general equations of motion to boundary layer equations, it is necessary that one of the coordinate axes coincide with the preferred direction of motion. This naturally takes place in the case of a rectilinear boundary of the region. This coincidence is not obtained for a curvilinear boundary in a Cartesian system of coordinates. The difficulty here is overcome because of the use of flow coordinates that permit one to reduce the problem to the consideration of the flow in a half-plane.

With sufficiently general premises, the initial equations of motion and the continuity equations are written in the Cartesian system as follows:

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=\frac{\partial}{\partial x}k_x\frac{\partial u}{\partial x}+\frac{\partial}{\partial z}k_z\frac{\partial u}{\partial z}-\frac{1}{\rho}\frac{\partial p}{\partial x}+F; \qquad (5)$$

$$u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=\frac{\partial}{\partial x}k_x\frac{\partial w}{\partial x}+\frac{\partial}{\partial z}k_z\frac{\partial w}{\partial z}-\frac{1}{\rho}\frac{\partial p}{\partial z}-g; \qquad (6)$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0. \qquad (7)$$

Here p is the pressure, ρ is the air density, and F is the Coriolis force. The longitudinal component of the exchange coefficient k_x was introduced into the equations of motion, since in the Cartesian coordinate system it is impossible to separate the preferred direction of motion. In keeping with the above, we switch to the system of flow coordinates $\phi=\phi(x, z)$ and $\psi=\psi(x, z)$.

Using the relation $\frac{\partial f}{\partial x}=u_\Pi\frac{\partial f}{\partial \varphi}+w_\Pi\frac{\partial f}{\partial \psi}$ and the analogous expression for $\frac{\partial f}{\partial z}$, we transform the main operators in (5) and (6) in the following manner:

$$-u_\Pi w_\Pi\frac{\partial}{\partial\psi}(k_x-k_z)\frac{\partial f}{\partial\varphi}+\frac{1}{2}(k_x-k_z)\frac{\partial\left(u_\Pi^2-w_\Pi^2\right)}{\partial\varphi}\frac{\partial f}{\partial\psi}-$$

$$-\frac{1}{2}(k_x-k_z)\frac{\partial\left(u_\Pi^2-w_\Pi^2\right)}{\partial\psi}\frac{\partial f}{\partial\psi}.$$

$$u\frac{\partial f}{\partial x}+w\frac{\partial f}{\partial z}=(uu_\Pi+ww_\Pi)\frac{\partial f}{\partial y}+(wu_\Pi-uw_\Pi)\frac{\partial f}{\partial\psi};$$

$$\frac{\partial}{\partial x}k_x\frac{\partial f}{\partial x}+\frac{\partial}{\partial z}k_z\frac{\partial f}{\partial z}=u_\Pi^2\left(\frac{\partial}{\partial\varphi}k_x\frac{\partial f}{\partial\varphi}+\frac{\partial}{\partial\psi}k_z\frac{\partial f}{\partial\psi}\right)+$$

$$+w_\Pi^2\left(\frac{\partial}{\partial\psi}k_x\frac{\partial f}{\partial\psi}+\frac{\partial}{\partial\varphi}k_z\frac{\partial f}{\partial\varphi}\right)-u_\Pi w_\Pi\frac{\partial}{\partial\varphi}(k_x-k_z)\frac{\partial f}{\partial\psi}- \qquad (8)$$

If the forms of the topography studied are not very steep, the value of k_x is close to the value of the exchange coefficient along the direction of the streamline. However, turbulent mixing along the flow plays a small part in comparison with advective transport. Therefore, the k_x values should not have any appreciable influence on the solution to the problem. Hence, no large error will be introduced by the assumption that $k_x \approx k_z = k$, and in addition, it considerably simplifies expression (8). The initial system (5)-(7) can then be written in the form

$$a\frac{\partial u}{\partial\varphi}+b\frac{\partial u}{\partial\psi}=v^2\frac{\partial}{\partial\psi}k\frac{\partial u}{\partial\psi}-\frac{u_\Pi}{\rho}\frac{\partial p}{\partial\varphi}+\frac{w_\Pi}{\rho}\frac{\partial p}{\partial\psi}+F; \qquad (9)$$

$$a\frac{\partial w}{\partial\varphi}+b\frac{\partial w}{\partial\psi}=v^2\frac{\partial}{\partial\psi}k\frac{\partial w}{\partial\psi}-\frac{w_\Pi}{\rho}\frac{\partial p}{\partial\varphi}-\frac{u_\Pi}{\rho}\frac{\partial p}{\partial\psi}-g; \qquad (10)$$

$$u_\Pi\left(\frac{\partial u}{\partial\varphi}+\frac{\partial w}{\partial\psi}\right)+w_\Pi\left(\frac{\partial w}{\partial\varphi}-\frac{\partial u}{\partial\psi}\right)=0, \qquad (11)$$

where

$$a=uu_\Pi+ww_\Pi,\quad b=wu_\Pi-uw_\Pi,$$
$$v^2=u_\Pi^2+w_\Pi^2.$$

We further introduce the new variables

$$u_1=a/v^2,\qquad u_2=b/v^2. \qquad (12)$$

We then transform equations (9)-(11) as follows. We multiply the equation obtained from (9) by u_Π, and that obtained from (10) by w_Π, and add. We then multiply the first equation by w_Π and the second by u_Π, and add again.

We thus obtain a system of equations of motion for the dimensionless components of the moving velocity:

$$u_1\frac{\partial u_1}{\partial\varphi}+u_2\frac{\partial u_1}{\partial\psi}+\frac{u_1^2+u_2^2}{v}\frac{\partial v}{\partial\varphi}+\frac{\partial}{\partial\psi}k\frac{\partial u_1}{\partial\psi}+$$
$$+\frac{2k}{v}\frac{\partial v}{\partial\psi}\left(\frac{\partial u_1}{\partial\varphi}-\frac{\partial u_2}{\partial\psi}\right)+\frac{1}{v}\frac{\partial k}{\partial\varphi}\left(u_1\frac{\partial v}{\partial\psi}+u_2\frac{\partial v}{\partial\varphi}\right)-$$
$$-\frac{1}{\rho v^2}\frac{\partial p}{\partial\varphi}+\frac{Fu_{\text{п}}-gw_{\text{п}}}{v^4};$$
$$u_1\frac{\partial u_2}{\partial\varphi}+u_2\frac{\partial u_2}{\partial\psi}+\frac{u_1^2+u_2^2}{v}\frac{\partial v}{\partial\psi}=\frac{\partial}{\partial\psi}k\frac{\partial u_2}{\partial\psi}+$$
$$+\frac{2k}{v}\frac{\partial v}{\partial\varphi}\left(\frac{\partial u_2}{\partial\varphi}-\frac{\partial u_1}{\partial\psi}\right)-\frac{1}{v}\frac{\partial k}{\partial\psi}\left(u_1\frac{\partial v}{\partial\varphi}-u_2\frac{\partial v}{\partial\varphi}\right)-$$
$$-\frac{1}{\rho v^2}\frac{\partial p}{\partial x}-\frac{gu_{\text{п}}+Fw_{\text{п}}}{v^4}. \tag{13}$$

Evaluating the terms in (13) and carrying out the usual simplification of the boundary layer theory, we obtain

$$u_1\frac{\partial u_1}{\partial\varphi}+u_2\frac{\partial u_1}{\partial\psi}+\frac{u_1^2}{v}\frac{\partial v}{\partial\varphi}=\frac{\partial}{\partial\psi}k\frac{\partial u_1}{\partial\psi}-\frac{1}{\rho v^2}\frac{\partial p}{\partial\varphi}+\frac{Fu_{\text{п}}-gw_{\text{п}}}{v^4};$$
$$\frac{1}{\rho v^2}\frac{\partial p}{\partial\psi}+\frac{gu_{\text{п}}}{v^4}+\frac{u_1^2}{v}\frac{\partial v}{\partial\psi}=0. \tag{14}$$

Here it was assumed that the term Fw_{Π} is small compared to gu_{Π}. Eliminating ρ from (14), we find that

$$u_1\frac{\partial u_1}{\partial\varphi}+u_2\frac{\partial u_1}{\partial\psi}=\frac{\partial}{\partial\psi}k\frac{\partial u_1}{\partial\psi}+\frac{(1-u_1^2)}{v}\frac{\partial v}{\partial\psi}+\Lambda, \tag{15}$$

where $\Lambda=Fu_{\text{п}}/v^4$.

The continuity equation in variables u_1 and u_2 will assume the form

$$\frac{\partial u_1}{\partial\varphi}+\frac{\partial u_2}{\partial\psi}=0.$$

We will distinguish the inner boundary layer above the obstacle from the boundary layer in the forward flow. It is understood that at a sufficient distance from the effective range of the disturbance of the boundary, the moving velocities in the inner boundary layer should continuously change into the velocities of the forward flow. This can be taken into account by writing the boundary conditions as follows:

for $\varphi\to-\infty \quad u_1=u^0(\psi),\quad u_2=0;$

for $\varphi\to\infty \quad u_1=1.$

In addition, according to the boundary conditions, we should have

$$\text{for} \quad \psi=0 \quad u_1=u_2=0.$$

Here $u^0(\psi)$ is the distribution, in the forward flow, of the wind velocity normalized to the value of v for $\psi \to \infty$, i.e., to the velocity of the gradient wind.

The term Λ in (15) ensures the agreement of the wind velocity at the upper boundary of the inner boundary layer with the velocity of the forward flow at the same level. In addition, the presence of Λ in (15) ensures the fulfillment of the natural requirement that the solution of (15) describe the vertical wind velocity profile above a horizontally uniform terrain. At the same time, consideration of this term in (15) causes a certain complication of the problem. This is due to the fact that as a result of the action of the Coriolis force, in addition to the component of the wind velocity u, it is necessary to consider the y component of v, with $F = 2\omega_z(v-v_g)$, where ω_z is the vertical component of the angular velocity of rotation of the Earth, and v_g is the y component of the gradient wind.

Consideration of a terrain uniform in the direction of the y axis will permit a simplification of the solution to the problem if it is approximately assumed that $v = v^0$, where v^0 is the y component of the wind velocity in the forward flow. We assumed that the air flow came in from a featureless uniform terrain, and therefore from the equation of motion it follows that

$$\frac{d}{dz} k^0 \frac{du^0}{dz} = 2\omega_z (v^0 - v_g). \tag{16}$$

where k^0 is the exchange coefficient in the forward flow.

For not very steep slopes, $u_n \approx v$. Then, according to (16), we obtain

$$\Lambda \approx \frac{1}{v^3} \frac{d}{dz} k^0 \frac{du^0}{dz}. \tag{17}$$

It suffices to give the form of the function u^0 approximately. In particular, it may be assumed that

$$u^0 = \ln \frac{\psi+\psi_0}{\psi_0} \Big/ \ln \frac{\psi_h+\psi_0}{\psi_0} \quad \text{for} \quad \psi \leqslant \psi_h$$

and

$$u^0 = 1 \quad \text{for} \quad \psi \geqslant \psi_h.$$

Here ψ_0 and ψ_h are, respectively, the roughness and height of the surface layer in the flow coordinates.

The dimensionless velocities u_1 and u_2 in the boundary layer are related to the real velocities u and w along the x and z axes as follows:

$$u(x, z) = u_1 u_{\text{п}} - u_2 w_{\text{п}};$$
$$w(x, z) = u w_{\text{п}} - u_2 u_{\text{п}}. \tag{18}$$

Above the boundary layer, $u_1 = 1$, $u_2 = 0$. Then from (18) it follows that $u = u_p$, $w = w_p$, i.e., the moving velocities of the boundary layer at its upper boundary continuously change into potential flow velocities.

Under the influence of the topography, a change takes place not only in the flow velocities, but also in the exchange coefficients. In order to take these changes into account, it is necessary to supplement the initial system of equations of motion with a relation defining the change of turbulence intensity. According to A. N. Kolmogorov [10], such a relation can be the equation of balance of the turbulence energy E:

$$u\frac{\partial E}{\partial x} + w\frac{\partial E}{\partial z} = \mathrm{Tr} + \mathrm{Df} - \mathrm{Di}. \tag{19}$$

Here Tr is the transformation component of the energy balance, determining the generation of turbulent eddies from the mean motion. In our case, in the study of motion in the plane (x, z) and assuming that $k_x \; k_z = k$,

$$\mathrm{Tr} = \frac{1}{r} k \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2.$$

$\mathrm{Df} = \alpha \frac{\partial}{\partial z} k \frac{\partial E}{\partial z}$ — being the diffusion term and $\mathrm{Di} = \frac{\beta E^2}{k}$ — the dissociation energy.

After simplifications of the boundary layer theory similar to those made above, the turbulence energy balance equation will assume the form

$$u_1 \frac{\partial E}{\partial \varphi} + u_2 \frac{\partial E}{\partial \psi} = \alpha \frac{\partial}{\partial \psi} k \frac{\partial E}{\partial \psi} +$$
$$+ kv^2 \left[\left(\frac{\partial u_1}{\partial \psi}\right)^2 + \frac{4u_1}{v} \frac{\partial v}{\partial \psi} \frac{\partial u_1}{\partial \varphi}\right] - \frac{\beta E^2}{v^2 k}. \tag{20}$$

The values of the dimensionless parameters α and β were obtained in [8] from published experimental data (α = 0.73, β = 0.046). The characteristic difference of (20) from the corresponding equation for the conditions of a horizontal uniform surface is expressed by the additional term $4kvu_1 \frac{\partial v}{\partial \psi} \frac{\partial u_1}{\partial \psi}$ in the transformed term. It can be stated that near the underlying surface, for all practical purposes

$$\frac{\partial v}{\partial \psi} = 1/R_b$$

where R_b is the radius of curvature of the boundary. Therefore, above convex portions of the surface, where $R_g < 0$, this term describes the decrease in the generation of turbulent energy, and above concave portions of the boundary (where $R_g > 0$), it describes the additional transformation of turbulent energy from the mean motion.

To determine the exchange coefficient, it is necessary to supplement the reduced system with a relation between E and k. In the general case, the following relation applies:

$$k = l\sqrt{E}, \tag{21}$$

where l is the mixing length. The use of (21) requires the introduction of a hypothesis for determining l. The problem under consideration deals only with the dynamic action of the topography on the turbulent regime. In this connection, we shall use an approximate scheme for generalizing the Kármán hypothesis of the mixing length, proposed in [8] for conditions of a horizontally uniform terrain

$$l = \varkappa\beta^{1/4} \frac{\Phi}{\frac{d\Phi}{dz}}, \tag{22}$$

where $\Phi = E/k$ and $\varkappa$ is Kármán's constant.

If l is eliminated from (21) and (22), the relationship between k and E is expressed by the differential equation

$$\frac{\partial k}{\partial z} - \frac{k}{E}\frac{\partial E}{\partial z} = \varkappa\beta^{1/4}E^{1/2}.$$

In flow coordinates, the operator $\frac{\partial}{\partial z}$ changes into $v\frac{\partial}{\partial\psi}$ and the latter relation assumes the form

$$\frac{\partial k}{\partial\psi} - \frac{k}{E}\frac{\partial E}{\partial\psi} = \frac{\varkappa\beta^{1/4}}{v}E^{1/2}. \tag{23}$$

As boundary conditions for (20) and (23), one can take the natural requirement that the turbulent energy E decays to zero when $\psi \to \infty$ (since this energy is assumed to be generated under the influence of the underlying surface) and the conditions following from the relation Tr = Di, which is fulfilled near the lower boundary ($\psi = 0$).

The formulated problem was solved numerically by using an M-220 computer. The initial calculations pertain to the case of an isolated hill.

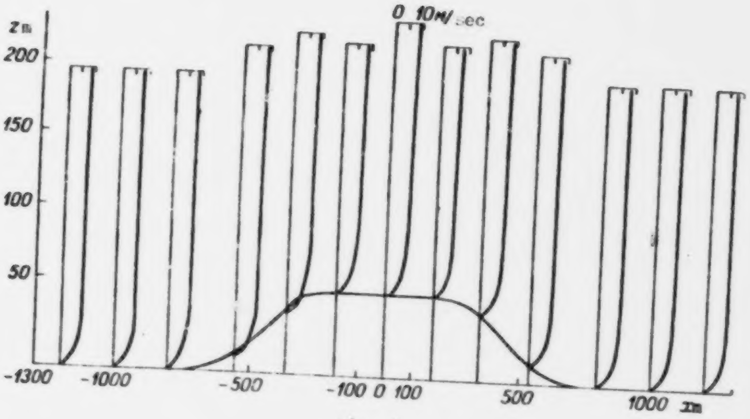

Fig. 3.

Figure 3 illustrates the vertical wind velocity profiles calculated for different parts of a hilly terrain (its outlines are shown in the lower portion of the figure). It is interesting to note the presence of a wind velocity maximum at a certain height, the formation of which is related to the interaction of the turbulent friction stress and Bernoulli pressure gradient. The presence and location of this maximum agree with the data of experiments on the stimulation of air currents [7].

Figure 4 shows the results of calculation of the change in the ratio of the wind velocity and exchange coefficient at two heights in different sections of the hill to their values in the forward flow (at $h_0 = 50$ m, $d = 250$ m, $\sigma = 500$ m, an underlying surface roughness $z_0 = 0.05$ m and a surface layer height $h = 100$ m). The results obtained also agree with existing measurement data under natural conditions [6, 11] and in a wind tunnel [7, 9]. In addition, the calculations show a number of fine effects that are difficult to observe experimentally; this applies particularly to the change of the exchange coefficient above the hilly ground.

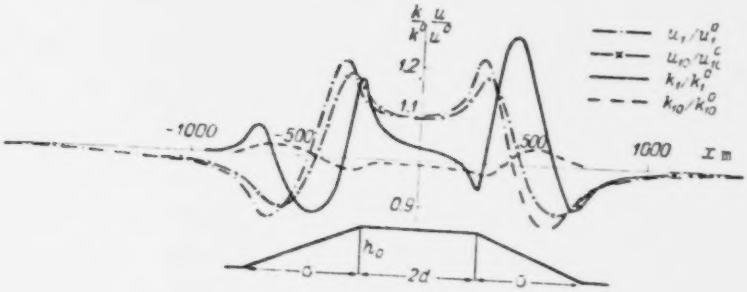

Fig. 4.

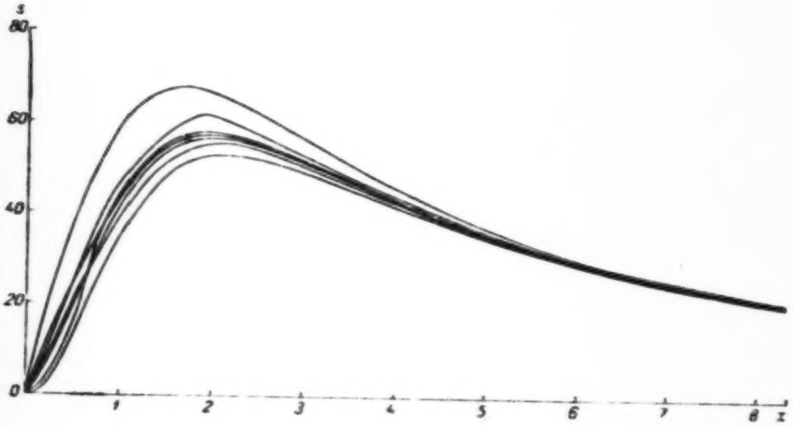

Fig. 5.

As a summation of this part of the study, Fig. 5 illustrates the results of calculations of the surface concentration from sources located at different points of a hilly terrain, but on the same streamline. In the calculations it was assumed that in the case of a flat surface, the source height $H_0 = 50$ m. The curves correspond to different locations of the source on the terrain. The results obtained make it possible to determine the differences in the distribution of surface concentrations and to estimate the range of applicability of the method of potential flows. Thus, from Fig. 5, plotted by taking the turbulent mixing in the boundary layer into account, one can conclude that when the source moves along the streamline, the maximum of the surface concentration changes, instead of remaining constant as in the case where the method of potential flows is used. For a source 100 m high and a hill 50 m high, such a change reaches almost 30% of the mean value.

Transformation of an Air Flow and Atmospheric Diffusion Above a Water Reservoir

In the vicinity of a series of large-capacity pollution sources, artificial water reservoirs are built for dumping spent water, industrial wastes, etc. In some cases, the water in such reservoirs is much warmer than the surrounding soil, for example in the vicinity of steam power plants. If it is also considered that the thermal characteristics of the water and soil differ appreciably, then for the most part the presence of water reservoirs causes a thermal disturbance in the air flows above them. In this connection, the results of the theory of transformation of an air flow above water reservoirs can be directly extended to other cases of thermal nonuniformity of the underlying surface, caused, for example, by differences in albedo, in the thermal conductivity characteristics of various parts of the soil, etc.

As in the preceding sections, the problem considered here is made up of two parts. The first consists in studying the transformation of an air flow above a nonuniform terrain and in determining the field of moving velocities and the exchange coefficient; the second consists in solving the corresponding equation of atmospheric diffusion of an impurity in the presence of a high source with coefficients obtained in the first part of the problem.

The initial system of equations for solving the given problem in accordance with the above and with a certain simplification related to the specifics of the problem under consideration is written as follows:

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=\frac{\partial}{\partial z}k\frac{\partial u}{\partial z}-\frac{1}{\rho}\frac{\partial p}{\partial x}; \tag{24}$$

$$u\frac{\partial\vartheta}{\partial x}+w\frac{\partial\vartheta}{\partial k}=\frac{\partial}{\partial z}k\frac{\partial\vartheta}{\partial z}; \tag{25}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z}=\frac{g\vartheta}{T}; \tag{26}$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0; \tag{27}$$

$$u\frac{\partial E}{\partial x}+w\frac{\partial E}{\partial z}=\alpha\frac{\partial}{\partial z}k\frac{\partial E}{\partial z}+k\left|\frac{\partial u}{\partial z}\right|^2-\frac{gk}{T}\frac{\partial\vartheta}{\partial z}-\frac{\beta}{k}E^2; \tag{28}$$

$$u\frac{\partial q}{\partial x}+w\frac{\partial q}{\partial z}=\frac{\partial}{\partial z}k\frac{\partial q}{\partial z}. \tag{29}$$

Here ϑ is the deviation of the temperature from its value in the forward flow. The remaining symbols are the same as in the preceding section.

The equation of turbulent energy balance (28) should be supplemented with relation (21), i.e., $k = l\sqrt{E}$. For a mixing length l in the case under consideration it is desirable to use the simplest Prandtl relation, usually employed for determinations in the surface air layer. According to Prandtl, $l=\varkappa(z+z_0)$, where z_0 is the roughness of the underlying surface. Here it will be assumed that z_0 has different values above dry land and a water reservoir, and thus essentially not only thermal but also dynamic disturbances of the boundary will be considered.

As boundary conditions for ϑ we shall assume that on the underlying surface it undergoes a jump equal to θ on passing from dry land to the water reservoir, and at an infinite distance from the underlying surface, ϑ decreases to zero. With regard to the concentration q we assume that on the underlying surface, the flow of impurity in the case of dry land and its concentration in the case of a water reservoir are equal to zero. Thus, for z = 0 on dry land $\vartheta=0,\ k\frac{\partial q}{\partial z}=0$; on the water reservoir $\vartheta=0,\ q=0$.

For the other unknown quantities in (24)-(29), the boundary conditions given are analogous to those in the preceding section.

As the initial conditions, in order to simplify the problem, it is convenient to assume that in the forward flow the thermal stratification is indifferent and by virtue of the definition of ϑ when x = 0, $\vartheta=0$. Accordingly, it may be approximately assumed that the initial distribution of the velocity u^0 with height is logarithmic, i.e., $u^0=\frac{v_*}{\varkappa}\ln\frac{z+z_0}{z_0}$, where v_* is the dynamic velocity, and when x = 0, u = u^0.

With regard to the air flow transformation, various parts of the formulated problem have been discussed by different authors. Having no survey to refer to, we will still indicate that on the whole, with the given formulation of the problem, its solution has not been obtained thus far.

In the system of equations (24)-(29), it is useful to switch to the deviation of the wind velocity from its initial values u^0, i.e., set u = u^0 + u'. Correspondingly, one can introduce the initial value E = E^0, where $E=E^0$, где $E^0=\frac{v_*^2}{\beta}$, and set E = $E^0(1 + r)$. We then have for the exchange coefficient $k=v_x l\sqrt{1+r}$. Hence, and also as a result of the exclusion of the pressure p from (24) and (26), equations (24) and (28) will be written as

$$(u^0+u')\frac{\partial u'}{\partial x}+w\frac{\partial u'}{\partial z}=\frac{\partial}{\partial z}k\frac{\partial u'}{\partial z}+\frac{v_*^2}{2\sqrt{1+r}}\frac{\partial r}{\partial z}-$$

$$-\frac{v_* w}{l}+\frac{g}{T}\int\limits_z^\infty\frac{\partial\vartheta}{\partial x}dz;$$

$$(u^0+u')\frac{\partial r}{\partial x}+w\frac{\partial r}{\partial z}=\alpha\frac{\partial}{\partial z}k\frac{\partial r}{\partial z}-$$

$$-\frac{\beta k}{v_*^2}\left[\frac{\partial u'}{\partial z}\left(\frac{2v_*}{l}+\frac{\partial u'}{\partial z}\right)-\frac{g}{T}\frac{\partial\vartheta}{\partial z}\right.$$

The remaining equations remain unchanged.

Calculations made by I. G. Gracheva showed that the self-similarity property is approximately fulfilled for the solution obtained. This means that the solution may be represented in the following form:

$$u'=u'_m(x)f_1(z/x);$$

$$\vartheta=\theta f_2(z/x);$$

$$r=r_m(x)f_3(z/x).$$

Here the zone of the air flow transformation above the water reservoir may be divided into two parts: in the initial part the chief influence on the transformation is exerted by the interaction of the buoyant force with the forward flow, and further development of the process depends on the way the exchange coefficient changes as a result of generation of turbulence above the water reservoir. Analysis of the initial system from the standpoint of dimensional theory showed that in the initial portion, the behavior of the solution is determined by the ratio $\frac{v_*^2 T}{g\theta x}$. In particular, for maximum values of u'_m and r_m, the following expressions may be written:

$$u'_m(x) \sim \frac{g\theta x}{v_* T}; \quad r_m \sim \frac{g\theta x}{v_*^2 T}.$$

In further transformation of the flow, a key role is played by the parameter θ/T, with $u'_m \sim \left(\frac{g\theta x}{T}\right)^{1/2}$, and the total turbulent energy $r \sim \frac{g\theta x}{T}$. These expressions can be used until the deviations of the meteorological elements are slight in comparison with the corresponding characteristics in the forward flow, and the boundary layer above the water reservoir is sufficiently thin.

The above conclusions are confirmed by results of numerical calculations of the transformation above a water reservoir, illustrated in Fig. 7 (for $\theta = +5°$, $v_* = 0.3$ m/sec).

Figure 6 shows the ratio $u'/u'_m(x)$ as a function of z/x for different x. It confirms the approximate self-similarity of the solution. Analogous relations hold true for other elements.

Figure 7 illustrates the behavior of the maximum deviation of the velocity $u'_m(x)$. It clearly shows two portions of the transformation: the initial one, where $u'_m \sim x$, and the region where $u'_m \sim \sqrt{x}$.

The common solution of equations (25)-(29) and of the atmospheric diffusion equation (30) makes it possible to determine the dissemination of an impurity near a water reservoir. Since absorption of the impurity takes place on the surface of the water reservoir, the concentration in the immediate vicinity of the water reservoir surface is very small, but it increases relatively rapidly with height. In addition, numerical calculations show that for water reservoirs of moderate length, the surface concentrations are restored very rapidly behind the water reservoir (i.e., reach the values they would have at the same distance above dry land).

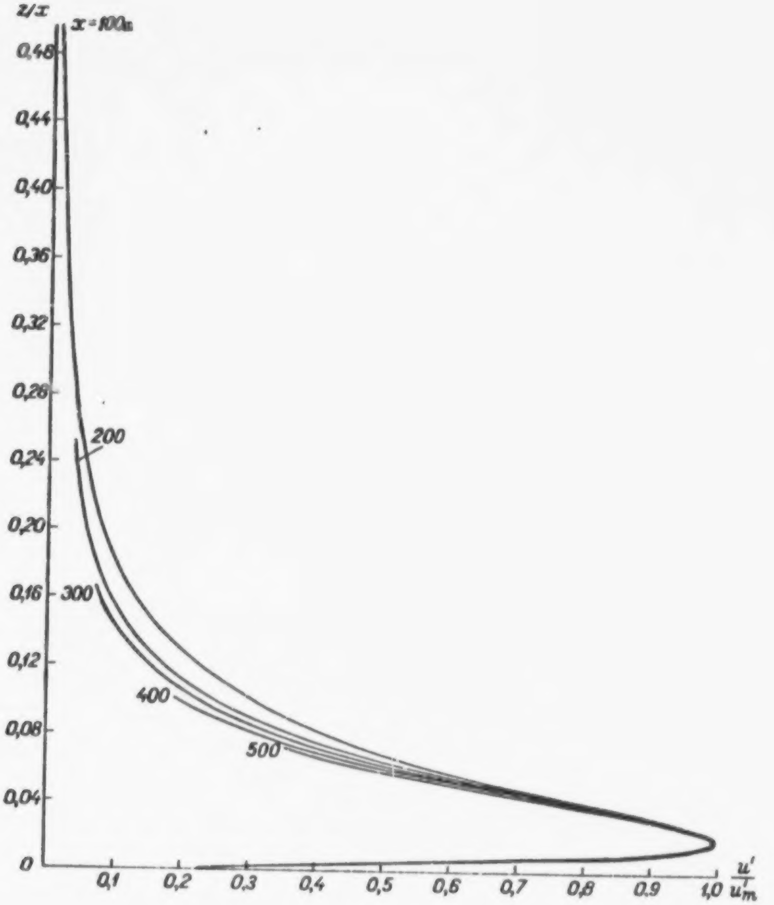

Fig. 6.

Moreover, since above a water reservoir ascending currents are usually present, and the turbulence coefficient is substantially increased, the surface concentrations of the impurity behind the water reservoir may also exceed the values reached above a horizontally uniform surface.

An illustration is provided by Fig. 8, which represents the distribution of the impurity concentration at the breathing level. It is evident that immediately beyond the water reservoir (crosshatched area), a sharp increase of the impurity concentration is observed.

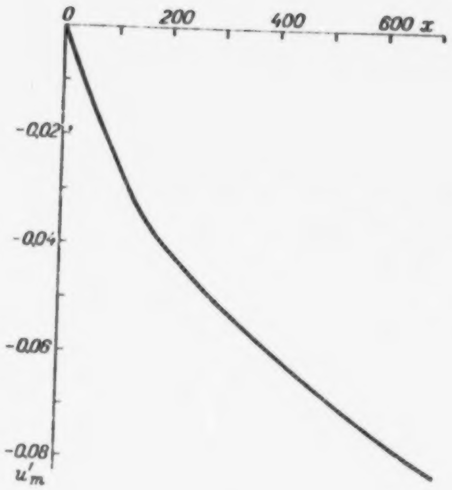

Fig. 7.

Combining the proposed methods makes it possible to investigate in detail the air flow transformation caused by changes in the roughness and albedo of the underlying surface, etc., and to evaluate the influence of various irregularities of the underlying surface on the dissemination of the impurity. It is necessary to bear in mind at this point that the change in the impurity concentration from industrial sources located on a nonuniform underlying surface may also be caused by the influence of the change in the wind velocity on the initial ascent of the impurity above the stacks. Therefore, for rugged as well as for featureless terrain, the unsafe wind velocity at which the surface concentration reaches the greatest values must be determined.

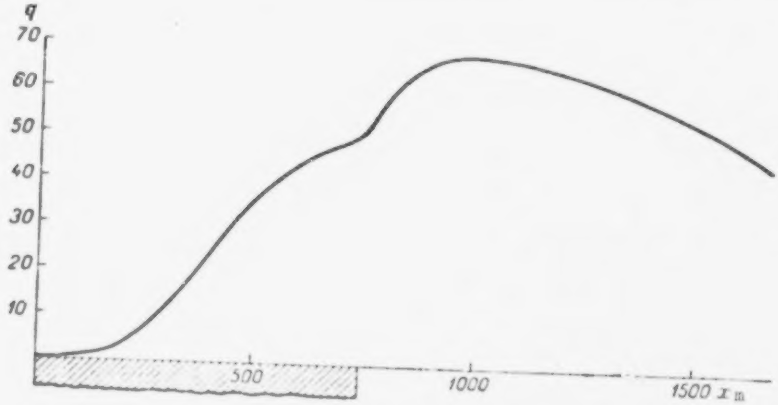

Fig. 8.

In conclusion, we should note that the methods presented in this study can be used to solve a whole series of meteorological and hydrodynamic problems (for example, in the study of air flow above an undulating surface, in calculating the heat emission from water reservoirs, cooling ponds, etc.).

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* Editor's note: References 12 and 13 are missing.

M. E. BERLYAND, E. L. GENIKHOVICH

ATMOSPHERIC DIFFUSION AND AIR CURRENT STRUCTURE OVER NON-UNIFORM UNDERLYING SURFACE*

As a rule, industrial enterprises and residential buildings are situated on a terrain with non-uniform characteristcs. In this case, studies on atmospheric diffusion should include such problems as the change of interaction mechanism of pollutant with underlying surface and the transformation of wind fields and exchange coefficient caused by complex terrain relief, water basins, change of albedo of underlying surface, etc.

In this work non-uniformity of underlying surface of two types is considered. One of them refers to unevenness of the terrain typical of hilly relief. The other is connected with temperature contrasts appearing on the boundary of water basins, for instance. In both cases the investigation is based on the solution of turbulent diffusion equation involving vertical and horizontal components of motion velocity and exchange coefficient over non-uniform surface.

To simplify the problem it is assumed that the underlying surface is uniform in the direction normal to average wind. Thus, we may connect pollutant concentrations of point and linear sources taking as proportional changes of horizontal components of exchange coefficient and wind velocity.

Coefficients of original diffusion equation are poorly studied functions of coordinates. Dynamic and thermal boundary disturbance and change of air current structure connected with it are essential, first of all, for the determination of changes of these coefficients. Therefore, pollutant concentration field and air current structure are determined simultaneously in this work.

Because of the complexity of atmospheric diffusion investigation in the conditions of cross-country, different approximate methods are suggested for solving this problem. One of the comparatively simple methods consists of construction of interpolation models for wind velocity and exchange coefficients. For this, the results of microclimatic observations at the height of 1—2 m are used which allow to estimate wind velocity growth at the windward slopes and its weakening at the lee slopes, etc. According to experimental data vertical wind profile in surface air layer slightly differs from logarithmic and this fact can be used for extrapolation of obtained results over higher levels. Vertical motion velocity component is found from continuity equation, and exchange coefficient as a first approximation is taken proportional to wind velocity.

Numerical integration of diffusion equation is carried out on this basis and calculations are fulfilled for some typical examples of hilly terrain. It follows from the calculations that the difference between maximum concentration values at different source location on the terrain with overfall of altitudes from 50 to 100m and an angle of slope inclination of 5—10° constitutes 30—50% for source heights of 50—200m, the differences decreasing with increasing of pollutant emission height (Fig. 1).

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* Editor's note: The abstract is presented as given in English with the original Russian article.

Another approximate method is connected with construction of potential velocity field of air current with the help of conform representation of curvilinear flow region on semiplane. It is supposed that the exchange coefficient in the diffusion equation is determined only by the stream function and the flow variables are introduced. Then this equation takes on the same form as in Cartesian coordinates for horizontally uniform terrain. So, for sources situated at the same flow line, surface concentration maximums have the same values. An error in the description of flow structure is decreasing with distance from underlying surface so far as turbulent viscosity effects are substantial in relatively thin layer near lower boundary. Maximum concentration corrections (30—50%) due to relief influence are received from calculations for hills and hollows with length of 1000m and overfall of altitudes of 100m. The application of this method is limited as it distorts flow velocity field near underlying surface, gives symmetric pattern of stream distribution on windward and lee slope, etc. So it is necessary to come over to more complete scheme taking into account the turbulent exchange.

To simplify such a scheme the theory of boundary layer of viscous liquid is used. For the reduction of motion equation to boundary layer equations it is necessary that one of the space axes coincides with prevailing motion direction. Such coincidence is not obtained at curvilinear boundary in Cartesian coordinates. Thus, flow variables are used which allow to reduce the problem to stream consideration in semiplane. To take into account exchange coefficient variations under the influence of relief, motion equation system is supplemented with the equation of turbulent energy balance. The latter contains an additional summand in transformative term depending on the radius of boundary curvature in contrast to turbulent energy equation for conditions of the flat ground. This summand describes the decreasing of turbulent energy generation over convex parts of the surface and an additional transformation of turbulent energy from the mean motion over concave parts. Besides, the correlation between turbulent energy, exchange coefficient and mixing path is taken into consideration.

The solution of the problem is obtained with the help of electronic computer M-220 The first calculations were carried out with respect to an isolated hill. According to obtained results, at a certain height the wind velocity maximum connected with interaction of turbulent friction stress and Bernoulli's pressure gradient is noted.

The wind velocities and exchange coefficients at different heights in different cross-sections over the hill are given in Fig. 4. The obtained data are conformed with measurement results in field experiments [6, 11] and in wind tunnel [7, 9]. At the same time some effects which are discovered by experiment can be seen from calculations.

Especially this refers to exchange coefficient variations over hilly terrain.

The obtained results allow to estimate applicability of potential flow method. So, from Fig. 6 one can conclude that at source dislocation along flow line the surface concentration maximum changes, and while using potential flow method it stays constant. This change achieves nearly 20—30% of average value for a source with height of 30—50m and a hill 50m high.

Near some powerful pollution sources artificial water basins are created for throwing off tail water, processing wastes, etc. In some cases water in such basins is much warmer than surrounding soil, for instance near thermal power plants. The problem solved here consists of two parts. The first part is the investigation of air stream transformation over non-uniform terrain, i. e. over heated water basin, and in the determination of wind velocity field and exchange coefficients. It includes solution of equations of motion, continuity, heat influx, and turbulent energy balance. The second part consists of solution of corresponding atmospheric diffusion equation with coefficients received in the first part of the problem for the point source.

As boundary conditions for temperature, it is assumed that on underlying surface, $z=0$, the temperature undergoes a jump while passing from land to water basin. The influence of this jump fades out to zero at infinity. It is accepted that at $z=0$ pollutant flow over the land and pollutant concentration over the water basin are equal to zero. As initial conditions for the purpose of simplification, the temperature stratification is supposed to be indifferent in free stream, and wind velocity variations with height are described by logarithmic law.

The results of calculations with the help of computer M-220 showed that the property of self-similarity is fulfilled approximately for the obtained solution. This is proved by calculation given in Fig. 6.

As pollutants are absorbed on the water basin surface, the concentration is very little in the immediate proximity of it. For not very long water basins numerical calculations showed that beyond the basin concentrations are restored very quickly and become of values which they would have been at the same distance over the land (Fig. 8). Moreover, as there are usually descending currents over the water basin and there is a marked increase in turbulence coefficient, pollutant concentrations in ground layer beyond the basin can even surpass those over horizontally uniform terrain.

Methods stated in this paper can be used in solving a number of meteorological and hydrodynamic problems, for instance, in air flow study over ruffled water surface, for calculation of heat output from water basins and pond coolers, etc.

PROCEDURE FOR CALCULATING THE POLLUTION OF THE ATMOSPHERE WITH DISCHARGES OF INDUSTRIAL PLANTS AND THERMAL POWER PLANTS

R. I. Onikul (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 70-81 (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

In the USSR, when industrial plants and thermal power plants are designed, a set of measures are taken aimed at reducing the noxious emissions into the atmosphere and bringing the impurity concentrations in the surface air layer down to the values permitted by sanitary standards (MPC). Considerable success has been achieved in the development of technological measures toward reducing noxious effluents and catching dust and other substances, especially in cases where their reuse is possible. However, for technical and economic reasons, a complete purification of the discharges can practically never be achieved at the present time. In many cases, no purification is made at all (for example, sulfur dioxide is not removed from the emissions of steam power plants).

Since it is impossible to prevent substantial emissions from a single source or a group of sources, it becomes necessary to construct high stacks. High stacks (up to 150-250 m) have been widely used at steam power plants, central heating-and-power plants, sintering ferrous and nonferrous metallurgical plants, cement plants, petroleum refineries, and chemical and other enterprises. Although the construction of purification equipment and stacks entails high expenditures, even greater economic problems arise in the establishment of the limiting output of the enterprises, which in many cases is primarily determined precisely by their noxious emissions. Thus, the planning of such expenditures should be based on scientific principles, adequate consideration being given to the amount of emissions and their parameters, which may affect the dispersal of the emissions, and also to the laws of atmospheric diffusion.

Sutton's formula is frequently used in design calculations of atmospheric pollution. A series of recommendations regarding the use of this formula are given in [1]. The chief drawbacks of Sutton's formula are described in [4] and elsewhere. Even the first comparatively brief expeditions of the Moscow Scientific Research Institute of Hygiene im. F. F. Erisman and other sanitation agencies in areas around steam power plants observed that the calculations differ substantially from observational data.

The most complete survey was made at the Shchekino State Regional Electric Power Plant (SREPP) (stack height, 120 m) in 1961-1963 in a series of expeditions by the A. I. Voyeykov Main Geophysical Observatory, conducted in collaboration with the Moscow Scientific Research Institute of Hygiene im. F. F. Erisman and other agencies [6, 12]. These studies noted that the calculations made with Sutton's formula gave results that were approximately one order of magnitude higher than the experimental data. The calculated dangerous velocities were found to be unrealistically low, and the concentrations of these velocities were lowest. The effectiveness of higher stacks (180-250 meters) could not be estimated by using these formulas, and this caused great difficulties in the expert evaluation of projects of steam power plants and industrial enterprises.

At the present time, the methods of calculation are required to permit the evaluation of not only the extent to which atmospheric pollution is affected by the stack height, temperature, and exit velocity of the flue gases, but also the influence of the dispersity of the discharges, and the degree of their centralization into high stacks and distribution over the terrain.

Since about 1960, the atmospheric diffusion and pollution section of the Main Geophysical Observatory, headed by M. Ye. Berlyand, has been conducting extensive theoretical and experimental studies aimed at the development of scientifically valid methods of calculation of atmospheric pollution. The theoretical studies are based on the solution of the equation of turbulent diffusion

$$u \frac{\partial c}{\partial x} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial c}{\partial z} + k_y \frac{\partial^2 c}{\partial y^2} - \alpha c. \qquad (1)$$

where c is the impurity concentration; the x axis is directed parallel to the wind, the y axis perpendicular to the wind in the horizontal plane, and the z axis vertically upward; u is the wind velocity; w is the resultant of the settling rate of the impurity and of the field of vertical velocities in the atmosphere, including the region of the smoke plume; k_z and k_y are the vertical and horizontal components of the turbulent diffusion coefficient; α is a parameter characterizing the degree of absorption of the impurity by the fog droplets, its radioactive decay, chemical transformations, etc.

Under normal conditions, the wind velocity is assumed to change with height according to the logarithmic law

$$u = u_1 \frac{\lg z/z_0}{\lg z_1/z_0}, \qquad (2)$$

where u_1 is the wind velocity at unit height z_1, and z_0 is the roughness of the underlying surface. The vertical component of the turbulent diffusion coefficient k_z is assumed to change with height according to a scheme with a "discontinuity"

$$k_z = \begin{cases} \nu + k_1 \frac{z}{z_1} & \text{for} \quad z \leqslant h \\ \nu + k_1 \frac{h}{z_1} & \text{for} \quad z > h. \end{cases} \qquad (3)$$

where ν is the coefficient of molecular diffusion, k_1 is the coefficient of turbulent diffusion at height z_1, and h is the height of the surface atmospheric layer.

The horizontal diffusion coefficient k_y is assumed to be proportional to the wind velocity (2)

$$k_y = k_0 u. \qquad (4)$$

The solution of equation (1), approximating expressions (2) and (3) being used for its coefficients, required the use of numerical methods and computers. Results of a numerical solution are given in [4-7].

In the numerical solution of equation (1), use was made of k_z and k_0 values characteristic of averaging times of the order of 2-3 min, and the concentrations should also be referred to this period of time. The switch to concentration $\bar{c}$ of a long (for example, 20-minute) sampling period is made by calculating the probability of fluctuations of the plume axis ω(ϕ)

$$\omega(\varphi) = \frac{1}{\varphi_0 \sqrt{2\pi}} e^{-\frac{\varphi^2}{2\varphi_0^2}}. \qquad (5)$$

Here   is the angle of deflection of the smoke plume axis from the mean direction for the sampling period T and $_0$ is the dispersion of the deflections of the smoke plume axis.

The maximum surface concentration $\overline{c_m}$ is described with sufficient accuracy by the following formula

$$\overline{c_m} = b \frac{Mk_1}{u_1 \varphi_0^2} \frac{1}{H^\beta}. \qquad (6)$$

where M is the output of the source, H is its height, and b is a constant; for h = 100 m and z_0 = 0.01 m, β = 2.3-2.5.

The coefficients w and k_z under dissected topographic conditions and in the zone of ascent of smoke plumes are determined by taking into account the solution of the system of equations of motion, heat influx and continuity [3, 7].

An approximate formula was obtained theoretically for calculating the effective ascent of a smoke plume ΔH

$$\Delta H = 1,5\frac{w_0 R_0}{u}\left(2,5 + \frac{3,3 g R_0 \Delta T}{T_e u^2}\right). \tag{7}$$

where u is the wind velocity at the wind vane height, w_o is the initial exit velocity of the flue gases, T_e is the absolute temperature of the ambient air, ΔT is the overheating of the flue gases, and g is the acceleration due to gravity.

In weak winds, the effective ascent of the plume increases rapidly, while the concentration decreases. A decrease in concentrations also takes place in strong winds owing to dilution of the flow directly at the source orifice. Therefore, there exists a "dangerous" wind velocity u_m at which the maximum impurity concentration is reached at the underlying surface.

The indicated survey of the Shchekino SREPP was carried out by using extensive meteorological observations including heat balance, lapse rate, and aerological measurements, and also by studying atmospheric pollution with sulfur dioxide and ash [12].

On the basis of theoretical and experimental studies, a procedure was developed in 1963 [10] that now constitutes a Government Standard Document for calculations of pollution of the atmosphere with emissions of steam power plants.

Basic assumptions on the character of the change of the parameters determining the turbulent scattering of an impurity in the atmosphere, made on the basis of mechanisms known in meteorology and refined by data of experimental studies at the Main Geophysical Observatory, were also checked in special diffusion experiments. The principal ones will be listed below.

1. A linear source of a polydisperse impurity, formed by an airplane at fixed heights from 100 to 600 m in a direction perpendicular to the wind. The character of the source excluded horizontal diffusion and the effective ascent of the smoke plume, so that it was possible to study the influence of the vertical component of the turbulent diffusion coefficient. Analysis of the solution of the "inverse" problem, i. e., the determination of the turbulent diffusion coefficient from the known discharge M and from the field of precipitation on the ground, confirmed the satisfactoriness of the use of the "discontinuity" scheme for k_z [11].

2. A point source of a polydisperse impurity with a finite time of action, produced by means of a 300-meter meteorological mast. In addition to checking the model for k_z, it permitted the study of the dependence of

the parameter ϕ_0, found by solving the inverse problem, on the meteorological conditions. The experiment demonstrated an accuracy of the model of horizontal impurity diffusion which is sufficient for practical purposes [9].

3. Photographing of the smoke plume of several large capacity steam power plants provided an experimental confirmation of formula (7) for the ascent of a smoke plume [6, 12].

Let us briefly consider the basic assumptions of a procedure, perfected in 1967, for calculating the dispersal of noxious emissions from stacks of large-capacity industrial sources [13], a procedure that constituted a development of [10].

On the basis of results obtained from a numerical solution, a procedure was developed for calculating the maximum atmospheric pollution from an isolated source for both the dangerous wind velocity u_m and other wind velocities. The use of the "superposition" principle also made it possible to propose a procedure for calculating atmospheric pollution from a group of sources.

All the formulas contained in the procedure pertain to unfavorable conditions of turbulent exchange. The basic characteristic of atmospheric pollution taken was the quantity c_m - the maximum surface concentration of the impurity under unfavorable conditions of turbulent exchange and at the unsafe wind velocity u_m.

The simplest case is that of N closely situated identical stacks, when c_m (in mg/m^3) is calculated from the formula

$$c_m = \frac{AMFm}{H^2} \sqrt[3]{\frac{N}{V \Delta T}}. \tag{8}$$

Here A is a coefficient dependent on the stratification of the atmosphere (sec $^{2/3}$ deg $^{1/3}$),

$$A = a \left(\frac{k_1}{u_1 \varphi_0} \right)_{\max}; \tag{9}$$

a is a constant equal to approximately 0.3 for conditions of a featureless terrain of medium roughness; $\left(\frac{k_1}{u_1 \varphi_0} \right)_{\max}$ is the largest of the values of the combination $\frac{k_1}{u_1 \varphi_0}$, that is possible in the given area at the dangerous wind velocity and that is usually observed in superadiabatic lapse rats.

Among current representations of the dependence of $\frac{k}{u_1}$ and Φ_0 on the meteorological elements u_1 and ΔT and also on the frequency of these values in different climatic regions, three zones are distinguished in the Soviet Union according to the value of the coefficient A: A = 200 for the Asian territory of the USSR, Caucasus, Urals, and Lower Volga; A = 160 for the European territory of the USSR (except the central part); A = 120 for the central part of the European territory of the USSR.

The quantity M is the amount of noxious substance discharged into the atmosphere (in g/sec); H is the geometric height of the stack above ground level (in m); N is the number of stacks; V is the volume of the gas-air mixture discharged (in m^3/sec).

The volume V is related to the diameter of the stack orifice D (in m), average exit velocity w_0 (in m/sec), and number of stacks N as follows:

$$V = \frac{1}{4}\pi D^2 w_0 N. \tag{10}$$

The quantity ΔT is the difference between the temperature T_g of the gas-air mixture discharged and the temperature of the ambient atmospheric air T_a (in °C); F is a dimensionless coefficient allowing for the settling rate of the noxious substances in the atmosphere.

As was shown by experimental studies made at thermal power plants, metallurgical enterprises, cement plants and other plants under ordinary operating conditions of the purification equipment, the characteristic distribution (of the dust and ash) is such that particles up to 30 mμ in size account for not more than one-half of the total weight of the dust. The remaining particles range in size from 30 to 100 mμ or more. The settling rate of each fraction of polydisperse dust (ash) may be calculated from the Stokes' formula.

Numerical solution of (5) shows that the maximum concentrations of light fractions are only slightly greater than the maximum concentration of the gaseous impurity for the same emissions. For heavy fractions, the maximum concentration is several times greater than the concentration of the gaseous impurity. The quantity F was determined as the weighted mean from the average weight distribution of the dust particles. For sulfur dioxide and other noxious substances whose settling rate is practically equal to zero, F = 1. For dust in the case of sufficiently thorough dust purification with an efficiency of not less than 90%, F = 2, and in the case of poorer purification, when the weight fraction of coarse dust particles increases, on the average, F = 2.5. Recent theoretical studies [8] have shown that strictly speaking, for sources with large H's, the coefficient F, in addition to depending on the particle size distribution of the dust, also depends directly on H.

Under dangerous meteorological conditions, for effective stack heights of the order of 400-500 m, $w = 0.2$-0.3 m/sec already corresponds to $F = 4$-5.

The quantity c_m depends substantially on the overheating of the flue gases ΔT. Here a key role is played by the value of ΔT entering into the denominator of the fraction under the cube root sign. The working formula was reduced to a form that is primarily convenient for calculations with large ΔT's. The results were corrected over a wide range of change of ΔT by introducing the coefficient m, whose dependence on the parameter $f = 10^3 \frac{w_0^2 D}{H^2 \Delta T}$ (in m/sec^2 deg) is shown in Fig. 1. Under the cube root sign there is also the quantity N/V, which characterizes the centralization of noxious emissions. The influence of this dependence may also be very significant. Thus, if instead of four stacks, the emission is directed into one stack of the same diameter, c_m will decrease by a factor of approximately 1.5. Therefore, the fewer stacks there are, the lower they can be. For example, four stacks 120 m high may be replaced by a single stack 100 m high.

When $0 \leqslant f \leqslant 6$, the parameter m differs from unity by not more than 10-20%, and c_m obeys a dependence that is extremely important in practice, i. e., it is inversely proportional to the square of the geometric stack height. The observation of this relation for hot emissions in studies made by the Main Geophysical Observatory and its subsequent experimental confirmation played a major part in the development of high-capacity steam power plants in the USSR (up to 1800-2400 MW and over for a stack height of 180-320 m) [6, 10].

One of the unfavorable meteorological factors is the minimum temperature difference ΔT. It is therefore recommended that an ambient air temperature T_a equal to the average temperature at 13 hours for the hottest month be used.

Since c_m pertains to unfavorable meteorological conditions, a criterion of the fulfillment of sanitary-hygienic standards is the relation

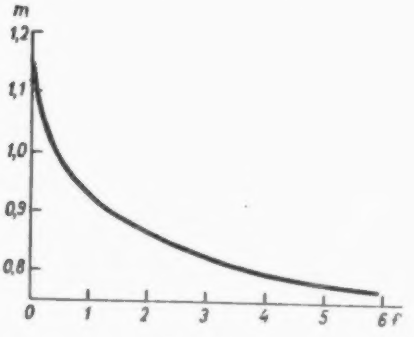

Fig. 1.

$$c_m \leqslant \text{MPC} \tag{11}$$

where MPC is the maximum permissible concentration, which usually pertains to a 20-minute sampling period.

In calculating c_m, it is not sufficient to use formulas for unfavorable meteorological conditions. It is no less important to consider the unfavorable conditions of emission of the noxious substances. Thus, in the combustion of fuel of different sulfur and ash contents, the largest values of these quantities should be employed in the calculations. The latter should also use actual values of the efficiency of purification equipment under ordinary operating conditions.

For large sources, to which the proposed procedure is extended, the maximum concentration c_m is reached at a distance x_m equal to approximately 20H, i. e., frequently beyond the boundaries of the industrial site and sanitary protective zone:

$$x = 20H. \qquad (12)$$

In the presence of a single high stack or N closely situated identical stacks, calculations with formula (8) are usually sufficient for a full evaluation of the adequacy of the steps taken toward protecting the air reservoir.

The calculations become more cumbersome in the presence of n sources that in the general case are characterized by different emission parameters and by a scattering over a sizeable territory. The calculations are then made in the following sequence.

For each source or group of N_1 identical and closely situated sources, one calculates the values of $c_{m\ i}$ and also the unsafe wind velocity $u_{m\ i}$ (m/sec):

$$u_{\ i} = 0{,}65 \sqrt[3]{\frac{V \Delta T}{N_1 H}}. \qquad (13)$$

The values of $u_{m\ i}$ obtained from this formula are in good agreement with the experimental data. Thus, for steam power plants u_m = 5-7 m/sec, and for smaller objects such as stacks of boiler houses and petroleum refineries, u_m = 2-3 m/sec.

We then calculate the weighted-mean dangerous wind velocity for the entire set of sources:

$$u = \frac{\sum_{i=1}^{n} c_{\ i} u_{\ i}}{\sum_{i=1}^{n} c_{\ i}}. \qquad (14)$$

As was shown by numerous calculations made at different wind velocities for large industrial complexes, the quantity u_{mw} always falls within a wind velocity range with atmospheric pollution which differs by only a few percent from the maximum c_m.

For each source, one calculates the maximum concentration $c_{m\mu}$ for $u = u_{mw}$ and the distance $x_{m\mu}$ at which it is reached:

$$c_{m u_i} = c_{m i} r_i; \quad x_{m u_i} = x_{m i} p_i. \qquad (15)$$

The quantities r_i and p_i are determined from $\frac{u_{mw}}{u_{mi}}$ with the aid of Fig. 2.

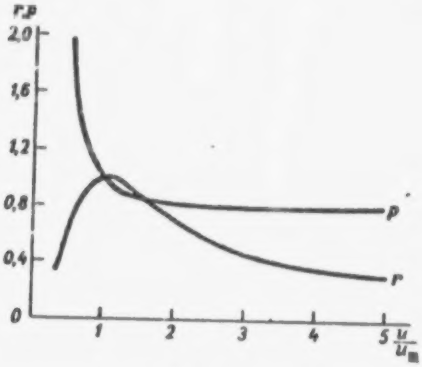

Fig. 2.

If the sources are located close to one another or are grouped along some line, then in seeking c_m, a graphical summation is used for the set of sources. A computer program has been written for calculations in the case of a large number of sources scattered over a considerable territory. To calculate the concentration c at a point located on the leeward side of the source (the coordinates of the point x_i, y_i in a coordinate system located in the i-th source and oriented with the x axis parallel to the wind), the following formula is used:

$$c = c_{m u_i} s_1 s_2. \qquad (16)$$

The quantity s_1 is determined from $\frac{x_i}{x_{m u_i}}$ with the aid of Fig. 3. The continuous curve is used for the case of a gaseous impurity, and also for dust when $\frac{x_i}{x_{m u_i}} \leqslant 2$. The dashed curve is used for dust when $\frac{x_i}{x_{m u_i}} > 2$.

The decrease of the concentrations in the direction perpendicular to the plume depends on the magnitude of s_2 (Fig. 4). The effects related to the scattering of the sources in the direction perpendicular to the wind are chiefly manifested on the plant site and in the sanitary protective zone. At distances from the plant in excess of 1-2 km, s_2 is close to unity. Therefore, the character of further decrease of the concentrations with distance depends mainly on the coefficient s_1, i. e., on the value of $\frac{x_1}{x_m u_1}$ and shape of the graph (Fig. 3).

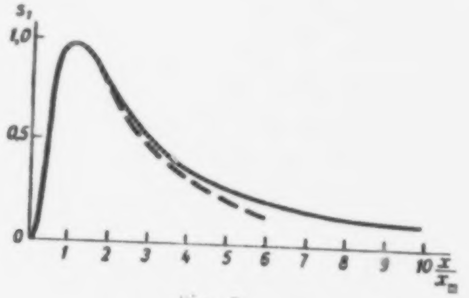

Fig. 3.

The impurity concentration at any point is taken equal to the sum of the concentration c from all the sources. In the calculations, the different velocities and directions of the winds are sorted out, and the maximum of the total concentration c_m is found.

In cases where it is impossible to obtain the MPC for residential areas beyond the territory of the plant, a sanitary protective zone is set up. The following formula is proposed for its calculation over a length L in the direction of prevailing winds:

$$L = L_0 \frac{P}{P_0}. \tag{17}$$

Here L_0 is the distance up to which the concentrations exceed the MPC, P is the frequency of winds of a given compass point (%) on the mean annual wind rose, and P_0 is the frequency of a single compass point for a circular wind rose, equal to 12.5%. For $P<P_0$, it is recommended that $L = L_0$ be used. In this approach, the sanitary protective zone additionally includes some areas with increased mean annual concentrations located on the leeward side [8].

Of the methods of presentation known to us, the one proposed above passed the most thorough checking tests on data obtained from surveys of atmospheric pollution in areas of about 20 major SREPP's and central heating and power plants located in different climatic zones, and also a series of chemical plants and ferrous and nonferrous metallurgival plants. On the whole, the agreement between the calculated and experimental data, primarily in c_m values and also in the character of the dependence on the metorological factors and coordinates, was found to be very satisfactory [6, 8, 12].

The formulas given above pertain primarily to frequent conditions of hot weather and dangerous wind velocity, when the largest c_m values are observed. The experimental data show that it is under these conditions that large concentrations are regularly observed in the vicinity of large sources. However, cases of dangerous atmospheric pollution under so-called anomalous stratification conditions have received widespread attention. The theoretical calculations also permitted an evaluation of the influence of various factors of "anomalous" stratification on atmospheric pollution [3, 8].

The heaviest air pollution in the presence of anomalous stratification would result from a possible combination of all the dangerous effects, the probability of which is comparatively low. For this reason, the procedure does not aim at the construction of stacks of a height so great that the concentrations would in no case exceed the MPC. It is proposed that under abnormally unfavorable meteorological conditions and in the presence of winds directed at residential areas, a short-term reduction of the noxious emissions be carried out. However, in areas with a high recurrence of dangerous weather conditions, as in the case of dissected topography, it is recommended that the stack height be increased in cases of individual expert examination of the industrial projects.

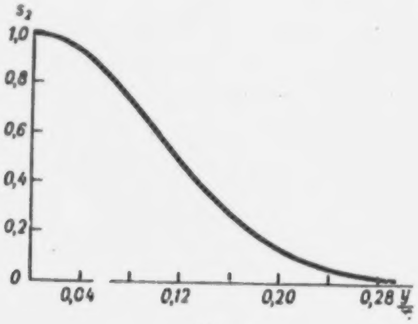

Fig. 4.

The procedure includes the formulation of a comparatively complete list of meteorological and sanitary data which should be included in the design specifications. Considerable attention is given to an objective assignment of the emission parameters and standardization of the calculations of atmospheric pollution. This substantially reduces the risk of impairing the sanitary requirements by decreasing the noxious emissions, neglicting dangerous weather conditions, or by formal use of theoretical formulas for the purpose of overcoming contradictions arising between the design agencies and sanitation agencies. Much remains to be done in order to achieve a coordination of the various departments in the calculation of the total atmospheric pollution with a timely consideration of the maximum capacity of the enterprises.

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R. I. ONIKUL

THE ESTIMATION TECHNIQUE FOR AIR POLLUTION BY EMISSIONS OF INDUSTRIAL ENTERPRISES AND POWER STATIONS*

On the basis of theoretical and experimental investigations of regularities of pollutant dispersion from industrial sources under different meteorological conditions, carried out in the Main Geophysical Observatory, *Provisional technique of calculation of pollutant dispersion (ashes and sulphur dioxide) in atmosphere from power station stacks* was compiled in 1963. Then the calculation technique was improved especially for use at enterprises with a great number of stacks with different emission parameters. In 1967 *Instructions on calculation of pollutant dispersion (dust and sulphur dioxide) contained in the industrial enterprise emissions* were published which are extended to emissions of metallurgic, oil-refining, and some other branches of chemical industry.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

Elaborate technique of air pollution calculation allows to determine stack height and performance coefficient of cleaning equipment which provide pollutant content in the atmosphere in the range of maximum permissible concentrations. In the case when it is impossible or economically unprofitable to build very high stacks and fulfill measures on emission decrease, the maximum permissible output of power station or plant is evaluated from the calculation. The means of background pollution evaluation and determination of boundaries of sanitary-protecting zone are given. Special attention is paid to standardization of emission parameter evaluation and calculation result representation.

The principal formulas refer to the conditions of most unfavourable combination of vertical and horizontal turbulent exchange intensity and dangerous wind velocity from the point of view of ground air layer pollution. Climatic conditions, emission dispersity, temperature and velocity of flue gases are taken into account in calculations. Calculations for a group of sources are carried out on the base of concentration superposition principle at "weighted mean" dangerous velocity and most unfavourable wind directions.

Calculation formulas are based on numerical solution of turbulent diffusion equation with the help of electronic computer. This allowed to consider, for the first time, changes of wind velocity and turbulent exchange coefficient with height, to investigate, in detail, dispersity influence of emitted aerosol, temperature inversions, and some other factors. The calculation formulas are in good agreement with observational materials received near some power stations, heat and power plants, metallurgic and chemical plants, and also on data of special diffusive experiments utilizing 300m meteorological tower, aircraft, etc. The comparison of technique of different countries showed that the technique used in the USSR has certain advantages in respect to generalization possibilities of this method to wider class of plants, complex relief conditions, etc.

STATISTICAL FORECASTING AVERAGE ATMOSPHERIC POLLUTION

A. Kaspshitzky* (Kasprzycki) PPR (Polish People's Republic)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 82-85, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The paper discusses the possibility of forecasting the average atmospheric pollution on the basis of predicted values of principal meteorological factors (such as wind direction and velocity, daily amount of precipitation, height and thickness of inversion layer, etc.). The results of the study are based on a statistical analysis of measurements of mean daily dust concentrations, conducted in 1963-1965 over a network of stations of the State Hydrometeorological Institute of the Polish People's Republic. The mean daily concentrations were determined by the gravimetric method on the basis of continuous measurements by means of membrane filters and vacuum oil pumps (with an output of about 100 m^3 of air per day).

In the study of floods, hydrological practice has established that many meteorological elements and also the maximum flow rates during a flood have an asymmetric statistical distribution. The latter can be reduced to a Gaussian distribution by means of the logarithmic transformation

$$z = \log(x + c), \tag{1}$$

where x is the primary random variable, z is a random variable with normal probability distribution, and c is some constant (it is usually assumed that c = 0, or this constant is determined graphically by random sampling). On the basis of his own studies, the author has come to the conclusion that in the case of a successful choice of the constant c, the transformation (1) normalizes at a confidence level of no less than 95% the extreme values of impurity concentrations as well as most meteorological-type random variables customarily measured. It may be stated that the random variable studied obeys the lognormal probability distribution.

The generalized lognormal distribution is uniquely determined by means of three parameters: m, σ and c; m and σ determine the normal distribution density N(z; m, σ) of the transformed random variable z, and c is a constant in (1). The best overall estimate of the three parameters describing the statistical distribution is obtained from sampling by the method of derived averages. It can be shown that the greatest-likelihood method is inapplicable in this case, since the probability function relative to c cannot be solved in the explicit form. If this method is used and if one considers that the random variable studied takes only positive values, the following relations can be obtained:

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* Editor's note: Certain inconsistencies between the transliteration of Russian phonetic spelling of non-Russian names and the accepted spelling of these names is unavoidable. For purposes of bibliographical referencing, the transliterated phonetic spelling is given first and the non-Russian spelling is given parenthetically.

$$m_3(\bar{x}+c)^3 - 3s^4(\bar{x}+c)^2 - s^6 = 0;$$
$$\sigma^2 = \frac{1}{\ln 10}\log\left[\frac{s^2}{(\bar{x}+c)^2}+1\right];$$
$$m = -\frac{1}{2}\sigma^2 \ln 10 + \log(\bar{x}+c). \qquad (2)$$

where $\bar{x}$ is the mean value, and s^2 and m_3 are the second and third central derived averages based on the sampling.

The first of equations (2) has only one real root which uniquely determines the parameter c. The other two equations permit the calculation of σ^2 and m.

In forecasting the mean daily atmospheric pollution as a function of meteorological elements, use is made of preliminary normalization of all random variables by means of transformation (1) and of the determination of the equation of linear regression for the transformed set of variables. Such a method permits an optimum utilization of the information contained in random sampling.

Let a random vector $z = (z_1, \ldots, z_n)$ be characterized by the vector of mean values $m = (m_1, \ldots, m_n)$ and by the covariance matrix

$$\mathfrak{M} = \left\| \begin{matrix} \sigma_1^2; & r_{12}\sigma_1\sigma_2; & \ldots; & r_{1n}\sigma_1\sigma_n \\ \cdot & \cdot & \cdot & \cdot \\ r_{n1}\sigma_n\sigma_1; & r_{n2}\sigma_n\sigma_2; & \ldots; & \sigma_n^2 \end{matrix} \right\|$$

Here σ_i is the standard deviation of the random variable z_i, previously normalized by means of (1), and r_{ij} is the correlation coefficient for the random variables z_i and z_j. Then, the following prognostic equation holds for the variable z_1 with given values of the remaining variables $z_2, \ldots, z_n$

$$m_{1w} = m_1 - \frac{M_{12}}{M_{11}}(z_2 - m_2) - \ldots - \frac{M_{1n}}{M_{11}}(z_n - m_n). \qquad (3)$$

where M_{1j} is the algebraic cofactor of element $\mathfrak{M}_{1j}$ in matrix $\mathfrak{M}$, M is the determinant of matrix $\mathfrak{M}$, and m_{1w} is the conditional mean value of the previously normalized variable being forecast.

Since in the case under consideration, the conditional distribution of the variable z_1 is normal, the quality criterion of the forecast may be the variance of the conditional distribution, given by the formula

$$\sigma_w^2 = \frac{M}{M_{11}},$$

or the total correlation coefficient of equation (3)

$$r_w = \sqrt{1 - \frac{\sigma_w^2}{\sigma_1^2}}.$$

The maximum value of z_w corresponds to the best forecast. In other words, the best forecast is obtained in the case of maximum correlation of the forecasting variables (predictors) $z_2, \ldots, z_n$ with the variable z_1 being forecast, and minimum correlation of the predictors with one another.

From data of measurements made in Poznan without preliminary normalization of the variables, the following relation was obtained:

$$s - 0{,}099 = -0{,}00466\,(O_p - 1{,}525) -$$
$$- 0{,}0905\,(V_{12} - 0{,}536) - 0{,}0153\,(H_{12} - 1{,}251). \quad (4)$$

Here s is the mean daily concentration of dust (in mg/m^3), O_p is the daily precipitation (in cm), $V_{1\,2}$ is the velocity of the surface wind at 12 hours on a scale of 10 m/sec, and $H_{1\,2}$ is the height of the inversion layer at 12 hours (in km). The overall correlation coefficient of this equation is 0.58.

If however the random variables s, O_p and $V_{1\,2}$ are first reduced by means of (1) to the normal distribution law and formulas (2) are used, the regression equation will take the form

$$\log + 1{,}074 = -0{,}210\,[\log(O_p + 0{,}047) + 0{,}988] -$$
$$- 7{,}14\,[\log(V_{12} + 8{,}4) - 0{,}953] - 0{,}058\,(H_{12} - 1{,}25). \quad (5)$$

The overall correlation coefficient for (5) is 0.64, i.e., greater than for (4).

From the completed analysis of the correlation between the mean daily concentration of dust and certain selected meteorological elements one can conclude that the use of (1) for the preliminary normalization of random variables makes it possible to increase the effectiveness of the linear regression equation, i.e., improve the use of the information contained in random sampling.

A. KASPSHITZKY

STATISTICAL PREDICTION OF MEAN AIR POLLUTION*

A prediction method of mean air pollution on the basis of daily mean dust concentration measurements by weight method, and standard measurements of such meteorological elements as wind direction and velocity, height and thickness of inversion layers, amount of precipitation, etc., is stated.

Approximation utilization of statistical microelement distributions and daily mean dust concentration with the help of generalized logarithmic distribution, the parameters of which are determined analytically, is the basis of this method.

On the basis of analysis of some variants of regression equation obtained from calculation on electronic computer it is shown that the transformation of random values on account of generalized logarithmic distribution increases correlation coefficient of prognostic equation for daily mean dust concentration.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

METHOD OF CALCULATING THE DEGREE OF ATMOSPHERIC POLLUTION

K. Budzinsky*.(Budzinski) PPR (Polish People's Republic)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 86-88, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

A method widely used in evaluating the degree of pollution of atmospheric air which is due to the action of local emission sources is one involving the calculation of characteristics of the impurity concentration field for certain given standard meteorological situations. The formulas used for this purpose in different countries and the empirical coefficients contained in these formulas differ substantially from one another and are the subject of constant discussions. This approach leads to substantial simplifications and appears to be justified when individual emission sources are compared. However, it cannot be used in comparing the results of calculations with measured data chiefly because these quantities have different physical meanings. The calculated values actually pertain to instantaneous values of impurity concentrations, whereas the results of measurements have the character of a statistical distribution. As is evident from analyses made by many investigators, this distribution can be approximately described by the lognormal law.

In order to be able to compare calculated and experimental data, it is necessary to conduct the calculations in such a way that the final result yields not individual values, but a statistical distribution of the concentrations or parameters characterizing this distribution (mean, median, standard deviation, etc.). To calculate the statistical distribution of the concentrations, one must know the statistical distribution of the parameters that have a substantial influence on the dispersal of an impurity in the atmosphere. Furthermore, one must know how to calculate the impurity concentration field for each specific set of values of the determining meteorological parameters.

In the simplest model, the impurity concentration in the vicinity of an isolated, continuously operating source may be considered dependent only on the wind velocity. We used Holland's formula for the thermal and dynamic ascent of gases leaving the stacks, and Sutton's formula for impurity dispersion. For fixed wind directions and given distances, transverse concentration distributions were calculated for different wind velocities. To each of these distributions there corresponds an appearance frequency equal to that of the corresponding wind velocity. By adding up the probability values obtained for the corresponding concentration ranges, one can determine the distribution function of the impurity concentrations.

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* Editor's note: Certain inconsistencies between the transliteration of Russian phonetic spelling of non-Russian names and the accepted spelling of these names is unavoidable. For purposes of bibliographical referencing, the transliterated phonetic spelling is given first and the non-Russian spelling is given parenthetically.

If several impurity sources are considered simultaneously, it is necessary to take into account the interaction of smoke plumes from different sources; this interaction will of course depend on the mutual arrangement of the sources and also on their parameters. Consideration of this fact leads to an increase in the volume of calculations, although it does not involve any fundamental changes in the calculation procedure. Let us note that as the number of emission sources located around an observation point increases, the calculated distribution of the concentration increasingly approaches the lognormal distribution.

Frequently, in the planning of industrial enterprises, the already-existing pollution level is taken into consideration. Within the framework of the proposed method, information on the achieved (actual) and expected (calculated) pollution level should be represented in the form of statistical distributions. The summation of these two distributions under the assumption of their mutual independence gives a resultant distribution characterizing the expected degree of distribution.

Results of calculations made by this method may be represented on a plan of the territory considered in the form of isolines of the same frequencies at which certain impurity concentrations are exceeded. Thus, one can not only distinguish the areas in which the permissible concentrations are exceeded, but also determine the time during which they are exceeded in the different areas.

As follows from the calculations performed, the wind rose appreciably affects the degree of atmospheric pollution, and must be taken into consideration when planning the arrangement of industrial enterprises in relation to other enterprises and residential sections. As an example, isolines of frequencies of excess over the concentration 0.9 mg/m^3 were calculated for an individual impurity source.

In conclusion, let us note that the calculation method presented does not require the use of certain formulas (Sutton's, Holland's, etc.) or certain values of empirical coefficients. As knowledge in this area progresses further, the introduction of other, more precise relationships, the consideration of thermal stratification in the calculation scheme, etc., will be possible. However, as follows from the examples cited, even the use of the simplest formulas will make it possible to obtain a larger amount of information and a more complete picture than if the methods currently employed are used.

K. BUDZINSKY

ON THE ESTIMATION OF AIR POLLUTION LEVEL*

For calculation of air pollution level in the neighbourhood of emission sources a method is suggested based on construction of concentration distribution function for each point in the space. The described method has some advantages in comparison with concentration calculation methods, usually used at present, for given meteorological situations as it gives the possibility to determine the occurence frequency of different concentration values. This is significant for interpretation of danger degree. Besides, it is convenient for comparison of the obtained results with experimental data.

The method mentioned above can be applied for pollutant distribution calculation both from a single source, and multiple sources. At some simplifying prerequisites this method can be used for air pollution estimation.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

ON THE DETERMINATION OF DIFFUSION PARAMETERS FOR ACTUAL LOCATIONS

A. Lehmann GDR (German Democratic Republic)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 89-98, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

1. INTRODUCTION

Artificially produced smoke trails for visualization and analysis of air flow fields have been in international use only in the last few years.

In the Meteorological Service of the German Democratic Republic, such artificially produced smoke trails were used initially for purely visual estimation of the air flow conditions in the orographically difficult regions for determining the location of industrial plants. From the changes in shape and position of the smoke trail, qualitative statements can be derived about the diffusion and dilution of the atmospheric stratification conditions determining air pollution. With the continuing improvement of stereophotographic equipment, [3] on one hand, and the evaluation of the photographic material obtained by semi-automated precision measuring equipment, as well as the possibilities of electronic data processing, on the other hand, the original goal of qualitative determination of special flow patterns typical of the location has been extended to a quantitative analysis of the flow pattern in the lower 300 m of the atmosphere. Information on the position and intensity of internal limiting layers can be obtained from analyses of frequency statistics [4].

The determination of such limiting layers and their characteristics is of particular importance for practical investigations, but also for theoretical investigations of problems of diffusion and dilution of injurious materials in the atmosphere.

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* Editor's note: This report was originally presented in German. Its English translation has been supplied by APTIC.

The great advantage of the application of smoke traces is that they actually provide complete information on the entire pattern of the vertical flow and diffusion pattern. Furthermore, we must not underestimate the advantage of their various possible applications at different locations, independent of previous long-term expensive investments for building carriers for conventional measuring devices. A disadvantage is the relatively high cost in the evaluation of the photographic material obtained in this way. In spite of partial automation of the evaluation process, only spot measurements can be processed, so that regression analysis appears necessary to generalize them.

2. ON THE DERIVATION OF DIFFUSION PARAMETERS FROM ARTIFICIALLY PRODUCED SMOKE TRAILS

From observations and measurements of the changes in shape and position of smoke clouds, statements can be derived about atmospheric diffusion. We can use:

(a) Smoke puffs, from which we can derive information on vertical and horizontal diffusion.

(b) Horizontal smoke plumes for derivation of diffusion parameters in the z-direction and, with observation from below, also in the y-direction.

(c) Vertical smoke streamers for determination of diffusion parameters in the x-direction through observations from the side, and in the y-direction through observations from the front.

The vertical smoke streamers make possible uninterrupted analysis of the horizontal diffusion vertical profile.

In our experiments in the flat country along the Baltic Sea coast, which was only partially disturbed by high growth, we used horizontal and vertical smoke streamers.

3. EXPERIMENTAL ARRANGEMENT

For production of vertical smoke streamers, we used 20 cm smoke bombs fired from a mortar to a height of about 300 - 350 m, where the smoke charge was ignited. Brilliant orange smoke streamers were produced during free fall. They can be readily evaluated when photographed on Orwocolor transparancy film in 13 x 18 cm format. The photographs were obtained synchronously with two aerial photography cameras from a distance of 800 - 1,000 meters, set by the camera optics. The cameras were specially adapted for use in terrestrial stereophotogrammetry. The aerial cameras are set up 80 - 100 m apart, parallel to the direction of spread of the smoke stream. The optical axes are horizontal and parallel. They are movable through an angle of ± 30 deg. in the horizontal plane. Photographs are made at equal time intervals. In the investigations so far, the time intervals have been 3 - 10 seconds, depending on the atmospheric conditions.

In our experiments to date, the aerial cameras were set perallel to the direction of flow because of our primary goal of establishing the structure of the wind field in the lower 300 m of the atmosphere. From the smoke pictures at hand, then, we can derive only the diffusion parameter in the x-direction. Diffusion in the y-direction can be only partially established, in the component which is determined by the bending of the smoke streamer perpendicular to the wind direction. Future experimental arrangements employing a second pair of aerial cameras should provide direct measurement of diffusion in the y-direction.

We first photographed horizontal smoke streamers in our study program in August, 1966. Smoke clouds with continuous smoke production for 3 - 5 minutes were produced with a captive balloon at heights between 60 and 200 m. The smoke charges were set at 2 meter intervals. The distance from the captive ballon was great enough (a) to ensure the safety of the balloon, and (b) to exclude falsification of the smoke plume patterns by perturbations in the flow conditions due to the balloon. Between the smoke experiments, measurements were made of temperature, humidity, and wind at the corresponding heights. Along with radiosonde launches from the nearby Greifswald radiosonde launching site, they provided sufficient characterization of the stratification conditions during the period of study.

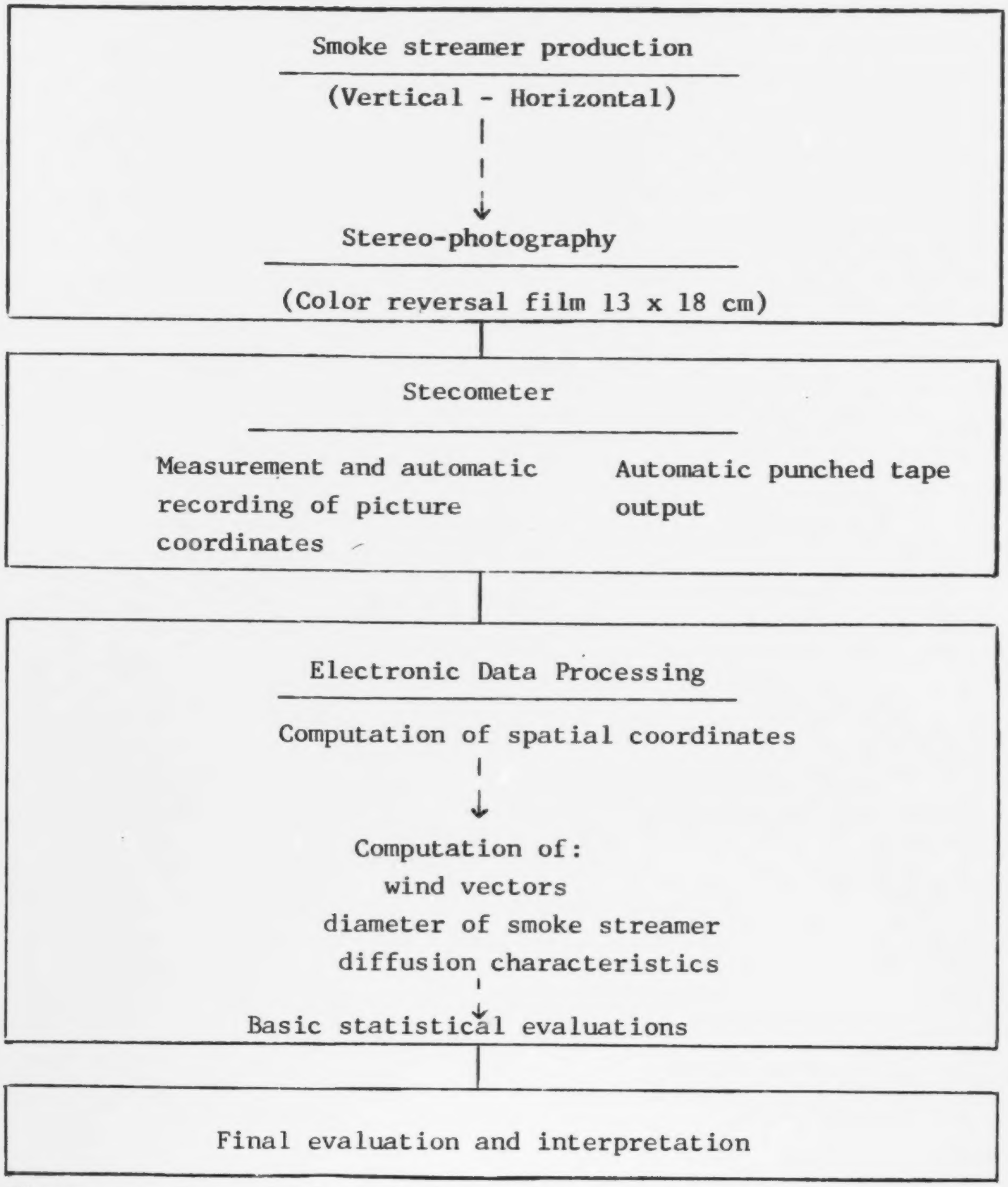
Smoke streamer production
(Vertical - Horizontal)
Stereo-photography
(Color reversal film 13 x 18 cm)
Stecometer
Measurement and automatic recording of picture coordinates
Automatic punched tape output
Electronic Data Processing
Computation of spatial coordinates
Computation of:
wind vectors
diameter of smoke streamer
diffusion characteristics
Basic statistical evaluations
Final evaluation and interpretation

Figure 1. General plan of the performance and evaluation of the experiments.

Figure 1 shows a general plan of the entire course of work in the experiments and their evaluation.

To derive the diffusion characteristics, along with the position coordinates of the center of the horizontal smoke plume, the thickness of the smoke plume perpendicular to its axis was measured at 10 m intervals from the source. With vertical smoke streamers, the corresponding measurements were made at 20 m height intervals.

4. THEORETICAL DERIVATIONS

4.1 Horizontal Smoke Plumes

In derivation of diffusion characteristics from the smoke plume pictures, we proceeded from the assumption that the concentration distribution of a smoke plume from a continuous point source can be described by the formula

$$C(x, y, z) = \frac{Q}{2\pi\sigma^2 u} \exp\left\{ -\frac{y^2 + z^2}{2\sigma^2} \right\}. \qquad (1)$$

The contour of the smoke plume is given by a constant integral value of the concentration distribution along the line of sight, i. e., along the y-axis. Thus we can from Formula (1) derive a functional relation between the thickness of the smoke plume and the diffusion [2, 5]

$$D^2 = 4\sigma^2 \ln \frac{K}{\sigma^2}. \qquad (2)$$

The symbols here are

C = concentration of harmful material
Q = source productivity
σ = dispersion
u = wind velocity at the altitude of diffusion
x, y, z = cartesian coordinates, with x in the direction of flow
D = diameter of the smoke plume perpendicular to its axis.

The constant K can be defined as 0.6796 D^2_{max}. This derivation applies with the assumption of Gaussian concentration distribution in the smoke plume perpendicular to the wind direction. This assumption is certainly not fulfilled for momentary distributions, but it is valid, with sufficient accuracy, as is known from the literature, for a time-average. As can be shown [1], the square of the deviation of the time-averaged concentration distribution in a smoke plume can be described by the arithmetic mean of the squared deviation of the instantaneous distributions, referred to the time-averaged smoke plume axis. Analysis of the variations, analogous to the method well known in mechanics as Steiner's law, shows that the square of the desired dispersion of the time-averaged smoke plume is equal to the sum of the squares of the deviations of the instantaneous smoke plume axes σ^2_{mz} and the arithmetic mean square of the instantaneous concentration distributions referred to the instantaneous axes $\bar{\sigma}^2_{\xi}$.

$$\sigma_z^2 = \overline{\sigma_\xi^2} + \sigma_{mz}^2. \qquad (3)$$

From the smoke plume photographs, it is simple to derive σ^2_{mz} from the deflections of the instantaneous axes from the source height, while the law stated previously applies for $\bar{\sigma}^2_{\xi}$.

$$D^2 = 4\sigma^2 \ln \frac{0{,}6796 D^2_{max}}{\sigma^2}.$$

By D^2 we mean the square of the arithmetic mean of the diameter at the distance x from the source point.

4.2 Vertical Smoke Streamers

A vertical smoke streamer is essentially an instantaneous line source between the coordinates 0, 0, -H and 0, 0, +H, referred to a coordinate system having its origin at the midpoint of the line source.

$$C(x, y, z) = \frac{Q}{u\,(2\pi\sigma^2)^{3/2}} \exp\left\{ -\frac{x^2 + y^2}{2\sigma^2} \right\} \int_{-H}^{H} \exp\left\{ -\frac{z^2}{2\sigma^2} \right\} dz. \tag{4}$$

Assuming that the line source is infinitely extended in relation to the smoke puff contributing to the concentration distribution at a given height, the integral has the value $\sqrt{2\pi}\,\sigma$. From this we obtain a formula analogous to (1), and this or similar methods can be employed to derive the relations between the diameter of the smoke streamer and the dispersion. The appropriate quantities are then $\sigma_x^2, \bar{\sigma}_\xi^2$ and σ_{mx}^2. By means of the sterophotographic technique, the quantity σ_{my} can also be derived from the vertical smoke streamers, and we can compute the relations between σ_{mx}^2 and σ_{my}.

5. EXPERIMENTAL RESULTS

As the results of machine computation of the quantities σ_x^2 and σ_z^2 were not available at the proper time, we must limit ourselves to consideration of the individual components of vertical and horizontal diffusion and their dependence on time and space.

5.1 Horizontal Smoke Plumes

These results were obtained from measurements during anticyclonal conditions on 17 August 1966. The general meteorological situation showed a high pressure bridge over central Europe, in which the temperature stratification in the lower 300 m of the atmosphere was almost adiabatic. At the altitudes considered, the prevailing wind was from NNE at 3 - 4 m/s. Figure 2 shows the results of the calculations. They confirm the theoretical expectations that, as distance from the source increases, D^2 rises to a maximum and then drops off. We were unable to derive a closed mathematical expression for the course of D^2 because the relatively long and gentle rise suppresses the brief drop at the end of the curve in any regression calculation. Up to a distance of about 140 m, the course of the

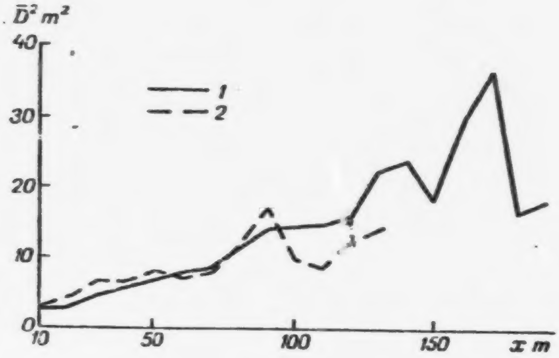

Figure 2. Diameter of the horizontal smoke streamer at heights between 140 and 180 m (1) and 65 and 105 m (2). 17 August 1966.

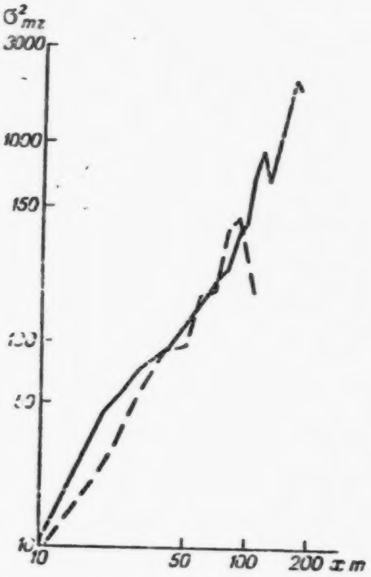

Figure 3. The course of σ^2_{mz} with increasing distance from the source.

curve can be approximated by a straight line. For x - 150 m it can be approximated by a second degree polynomial.

Evaluation of the lower smoke plume was not completely possible, as the view was limited by trees between the site of smoke production and the photographic baseline.

Figure 3 shows the course of σ^2_{mz} with increasing distance from the source. For the upper smoke streamer, the curve can be approximated by an exponential function. For the lower streamer, the curve drops off steeply after a maximum. This might indicate a limit to the size of the turbulence cell acting on the smoke plume, but orographic inhomogeneities may also be responsible for this. For technical reasons, the first experiment evaluated here was not performed in completely undisturbed country, but over an extended forest clearing. But the drop in the curve is based on too few measurements, and satisfactory interpretation must wait for evaluation of other experiments over flat land.

5.2 Vertical Smoke Streamers

These are the results of experiments performed on 20 and 21 August, 1966, over flat land at the Baltic Sea coast.

A low-pressure area over central Europe produced winds from the east to northeast with quasi-constant velocity of 5 m/s between 20 and 250 meters on 20 August, and an increase of the wind with height from 7 to 10 m/s on 21 August. (Figures 4 and 5). The

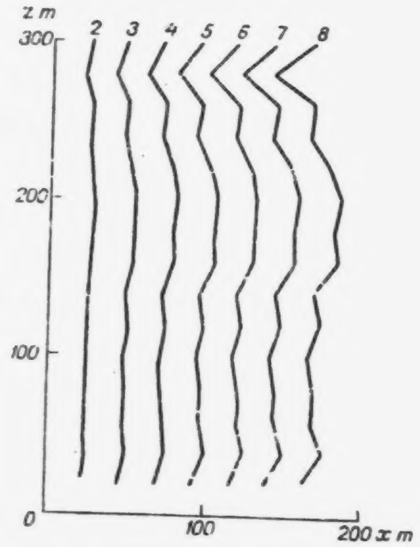

Figure 4. Results of studies of vertical smoke streamers on 20 August 1966

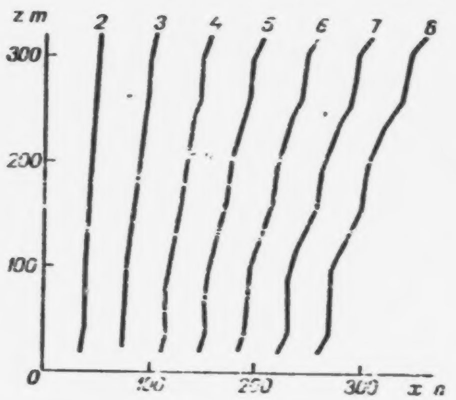

Figure 5. Results of studies of vertical smoke streamers on 21 August 1966.

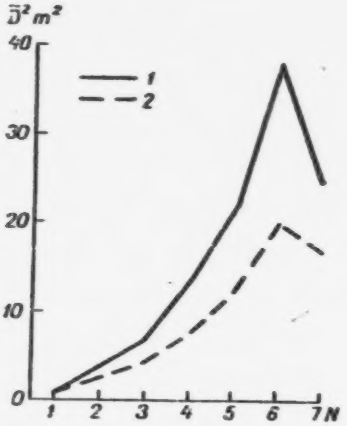

Figure 6. Squares of the diameter as a function of the diffusion time (phase) as an average for the heights:
20 to 80 m (1)
20 to 220 m (2)
20 August 1966.

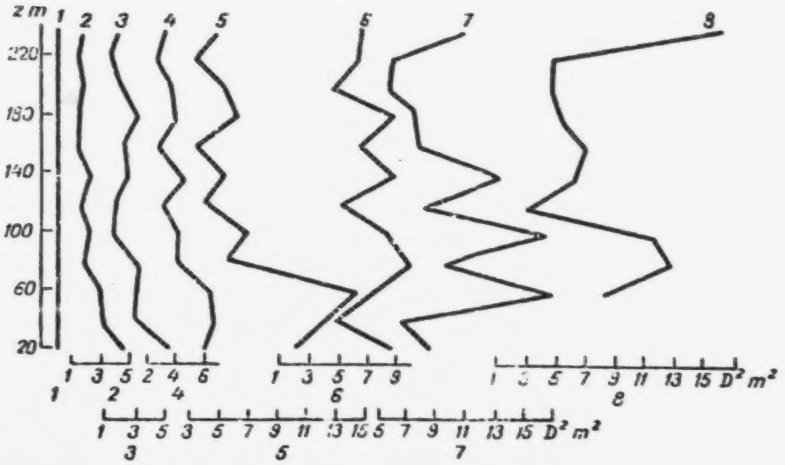

Figure 7. Square of the average smoke streamer diameter as a function of the height. 21 August 1966.

vertical temperature decrease was about 0.5°/100 m on 20 August and about 1°/100 m on 21 August.

As a demonstration of how the experimental results appear in detail, Figure 6 shows the square of the diameter after different diffusion times on an altitude plot (21 August 1966). The time intervals between phases were 5 seconds. The curves were not smoothed. The strong scattering of the squares in phases 6 and 7 is explained primarily by the beginning of break-up of the smoke streamer. In the final stage, it consists only of unconnected smoke balls. The measuring errors produced by the unsharpness of the decomposing smoke plume contours are hardly significant in comparison, as we could demonstrate with repeated measurements in the critical phases by different evaluators.

If we consider the behavior of the smoke plume diameter as an expression of horizontal diffusion, then from Figure 6, with all its fluctuations, we can clearly recognize several layers of qualitatively different diffusion conditions. In particular, the layer between about 60 and 120 m height is striking because of its increased tendency for intermixing, like the great increase in the smoke plume diameter above about 220 m height. Analogous results were also obtained in evaluations on other test days. If we consider the behavior of σ_{mx}^2 with height as a supplement to the smoke plume diameter measurements, then similar phenomena can be established, although the height positions of the layers do not agree in every case. But it appears that, in the vertical structure of the diffusion field, the indicated structure is similar to that which Kolbig [4] has described for the wind field. However, the material available is not sufficient for statistical investigations.

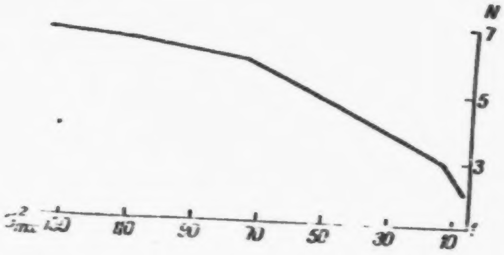

Figure 8. Scattering of the instantaneous axes of the smoke streamer at heights of 20 to 240 m. 21 August 1966.

In order to understand the relation of the basic characteristics of behavior of the smoke streamer diameter with distance from the point of origin, the squares of the diameters were averaged over the heights. The pattern obtained is shown in Figure 7. Of course, such averages are not valid for completely using the information content from vertical probes, but they are well suited for distinguishing the typical phenomena out of the many details.

Figure 8 shows the scattering of the instantaneous smoke plume axes, likewise as an average over heights, as a function of the phases, i. e., of the diffusion time. As for the horizontal smoke plumes, the curve can be described by an exponential function.

Not only D^2 but also σ_{mx}^2 show the same behavior in principle on the two test days (20 - 21 August 1966), but of different magnitudes. We believe that we cannot say anything about the effect of meteorological parameters on diffusion until we have more numerical data.

SUMMARY

Studies on the characterization of diffusion conditions were performed in the framework of an extensive investment plan on the Baltic Sea Coast. We have reported on the derivation of characteristics for atmospheric diffusion from stereophotographic instantaneous records of artificially produced horizontal and vertical smoke streamers.

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DETERMINATION OF DIFFUSION PARAMETERS FOR VARIOUS POINTS* (ABSTRACT)

A. Lehmann (German Democratic Republic)

The paper describes a method for studying the wind profile up to a height of ~ 300 m and atmospheric diffusion parameters playing an essential role in the study of atmospheric pollution.

The recording apparatus used consisted of two aerial photographic cameras specially adapted for land stereophotogrammetric photography. The photographs were taken with Orwocolor type reversible color film with a frame size of 13 x 18 cm. The wind gauges used were smoke cartridges 20 cm in size which during

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* This is a translation of the original Russian abstract accompanying this German paper.

their free fall give bands of orange color. Knowing the time-ordered coordinates of the displacement of the smoke bands, one can obtain the wind velocity profile, and from the expansion of the visible outline of a smoke plume, determine the parameters of diffusion in the direction of the wind.

Tests of the method by means of horizontal smoke bands were conducted in August 1966. For this purpose, the smoke charges (time of action, 3-5 min) were lifted by means of a balloon to heights of 60 to 200 m; the charges were placed on the balloon rope in such a way that the balloon itself was safe, and the influence of the balloon on the spreading of the smoke bands was excluded. The profiles of the horizontal smoke plumes obtained made it possible to determine the diffusion coefficients in the vertical direction, using the functional dependence between the width of the plume and the diffusion coefficient.

In conclusion, an analysis is given for several measurements of parameters of vertical and horizontal diffusion parameters as a function of space and time.

TURBULENCE IN THE LOWER 500 M LAYER AND DIFFUSION OF IMPURITIES

I. V. Vasil'chenko and P. A. Vorontsov (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 99-108, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The dispersion of emission products from industrial facilities and other sources of atmospheric pollution is determined by the state of the atmosphere both at the underlying surface and in higher layers. For this reason, when the studies considered below were formulated at the A. I. Voyeykov Main Geophysical Observatory, the need immediately arose for special aerological investigations. Aerological observations combined with surface meteorological observations were aimed at promoting the understanding of the processes of impurity diffusion under various natural conditions. Network aerological observations, chiefly the radio sounding method, are still insufficiently accurate in boundary layer measurements of air temperature and in part, wind velocity, and the turbulence characteristics are not measured by these methods at all. Hence it was necessary to develop special methods for studying the boundary layer or to adapt the existing ones.

To solve the formulated problem, use was made chiefly of balloon, airplane and helicopter soundings and also reference pilot balloon observations, the procedure and apparatus for which have been described in detail in a monograph [4]. Here we will indicate only that two types of instruments were lifted by a 110 m^3 captive balloon:

(a) A meteorograph with recording of temperature ($t°$), air humidity ($r\%$), atmospheric pressure (p mb), mean wind velocity ($\overline{u}$ m/sec) and longitudinal component of wind velocity fluctuations u'. The measurements were made up to a height of 500 m, the instrument being held for 5-minute periods at 25, 50, 100, 150, 200, 300, 400 and 500 m levels.

(b) An instrument recording the structure of the air flow to measure the longitudinal u' and vertical w' components of wind velocity fluctuations, the mean wind velocity ($\overline{u}$ m/sec), and atmospheric pressure (p mb). The ascents were usually carried out to a height of 300 m with 5-minute plateaus at 2, 100, 200 and 300 m levels.

In the airplane and helicopter were mounted a mechanical meteorograph and an electrometeorograph, which recorded p mb, $t°$, and $r\%$ on photographic film of an oscillograph, and also the overloads Δn to which the airplane and helicopter were subjected during flight and temperature fluctuations t'.

The choice of the above-indicated methods of observation in the atmospheric boundary layer was determined by the fact that they made it possible to determine experimentally, at different levels above the underlying surface, the most important meteorological parameters entering into both the equation of turbulent diffusion and the equation of turbulent energy balance. Furthermore, whereas balloon sounding permitted studies only above a single point to a height of 500 m, the use of a helicopter and light airplane permitted both vertical and horizontal soundings in the entire boundary layer, up to 1.5-2 km.

Numerous ascents of the captive balloon, airplane and helicopter, carried out in a number of areas of the Soviet Union and in different seasons, permitted the accumulation of extensive data on vertical temperature and wind profiles and also on fluctuations of these meteorological elements characterizing the structure of the air flow.

Balloon observations conducted in the vicinity of major thermal power plants permitted, in particular, the elucidation of a number of questions of importance from the standpoint of impurity diffusion. It was shown that the forms of smoke plumes are related in a definite manner to the characteristics of vertical distribution of temperature and wind [1], and that the wind profile frequency has a complex character and depends substantially on the thermal stratification [3].

Studies of the structure of the air flow showed, on the whole, that its space-time variations, and hence, the variations of turbulent energy are fairly variegated in character, but in general, the greatest turbulence intensity is observed in summer and in daylight hours.

The mechanism of formation of atmospheric turbulence is revealed most completely by analyzing the equation of turbulent energy balance and its various components. The process of generation, transport and dissipation of turbulent energy without consideration of the horizontal diffusion terms is described by the equation

$$\frac{dE}{dt} = \tau \frac{\partial u}{\partial z}(1 - \mathrm{Ri}) + \frac{\partial}{\partial z}(\overline{Ew'}) - \varepsilon. \qquad (1)$$

Equation (1) may be represented in the form

$$\frac{dE}{dt} = k\left(\frac{\partial u}{\partial z}\right)^2 + k_t g \frac{(\gamma_0 - \gamma_e)}{T} + \frac{\partial}{\partial z} k \frac{\partial E}{\partial z} - \varepsilon, \qquad (2)$$

where

$$E = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$$

is the kinetic energy of turbulent wind fluctuations along axes x, y and z, referred to unit mass, and σ_u and σ_w are root-mean-square values of u' and w' (hereinafter it will be assumed that $\sigma_v = \sigma_u$).

The quantities in the right member of (2) signify the following:

$$k\left(\frac{\partial u}{\partial z}\right)^2 = B$$

is the inflow of turbulent energy due to transformation of the main flow (dynamic factor), determined by the wind shift $\beta = \frac{du}{dz}$ and the magnitude of the turbulence coefficient k;

$$k_t = \frac{g(\gamma_0 - \gamma_e)}{T} = A$$

is the inflow-outflow of energy due to work done against Archimedes forces, i.e., the power of convection.

The sign of A is determined by the ratio of the equilibrium (γ_e) and observed (γ_0) vertical temperature gradients. The coefficient of eddy diffusivity k_t will hereinafter be assumed equal to the eddy viscosity coefficient k; ε is the rate of dissipation of turbulent energy, and according to [7], we will assume $\varepsilon = \frac{aE^2}{k}$, where α is a constant coefficient equal to 0.046;

$$\frac{\partial}{\partial z} k \frac{\partial E}{\partial z} = D$$

is the diffusion of turbulent energy, which according to [6] may be calculated from the simplified formula:

$$D_i = \frac{(k_{i+1} + k_i)E_{i+1} + (k_{i+1} + 2k_i + k_{i-1})E_i + (k_i + k_{i-1})E_{i-1}}{2|\Delta z|^2}, \qquad (3)$$

assuming E and k to be zero near the earth's surface.

Knowing the values of k and E at 100, 200 and 300 m levels, D can be calculated only for 100 and 200 m levels. The term dE/dt determines the inflow-outflow of kinetic turbulent energy between two segments of time. When dE/dt>0, the kinetic energy flows in, and when dE/dt<0, it flows out.

Below, we shall briefly consider the methods of calculation and general patterns of distribution of certain quantities entering into the terms of the equation of turbulent energy balance and indispensable for the calculation of all its components.

The quantity k, based on data of airplane soundings with recording of overloads, was calculated from A. S. Dubov's formula with a fluctuation frequency correction proposed by M. A. German:

$$k_z = \frac{w'^2 \tau V_a}{2}, \tag{4}$$

$$w' = \frac{b_\infty |\Delta n|}{\Delta \eta}, \tag{5}$$

where V_a is the air speed of the airplane; b_∞ is a transfer function relating the airplane overloads Δn to the vertical component of the wind velocity w'; η is a correction factor allowing for the fluctuation frequency; Δ is the density correction, and τ is the period of fluctuations in seconds.

Based on data of balloon sounding, k was calculated from Lyapin's formula [8]

$$k_z = \frac{w'^2 \tau_w \bar{u}}{2u'}, \tag{6}$$

where τ_ω is the time of retention w' of the same sign.

Some features of the calculation of k from balloon data should be mentioned. First, when u and u' are equal to zero, according to formula (6), k becomes zero or infinity. For this reason, it was calculated only for values of $u' \geqslant 0.1$ m/sec. Cases with still conditions and an even wind (without gusts) were excluded. Secondly, the time of retention of vertical fluctuations of the same sign τ_ω is determined by the eddy spectrum. As was shown by the experiment, the instrument recording the wind structure in the captive balloon frequently showed so-called short-period fluctuations with τ_ω=2-4 sec and simultaneously, long-period fluctuations, with τ_ω=20-40 sec. Only the long-period fluctuations were used in the calculation. In this case, in the boundary layer, the values of k calculated from formula (6) vary from units to tens of m^2/sec. In the calculations, k was averaged over a period of time of a few minutes, usually 2-3 min.

Treatment of balloon data for different conditions showed that in an air layer up to 300 m, for the vertical profile of k in unstable and indifferent stratification, the presence of a maximum at the level of 100 or 200 m is most characteristic. In stable stratification, an appreciable decrease of the absolute values of k is observed, and k remains practically unchanged in the 100-200 m layer. At low wind speeds, the values of k are relatively small; they rise with increasing wind velocity, but only up to certain limits, beyond which they may decrease, apparently because of a corresponding variation of the vertical temperature gradient, which at high wind speeds begins to decrease, and there is a corresponding decrease in k.

In addition to the vertical temperature and wind velocity profiles, the absolute values of k also undergo considerable changes as a result of a number of other factors: roughness of the underlying surface, orography of the terrain, and averaging period. In particular, in calculations of k from airplane data, when the averaging period was taken as 30 sec, the presence of appreciable fluctuations in k along both the vertical and the horizontal direction was demonstrated, so that the vertical section of the turbulence coefficient field was focal in character. Similar substantial fluctuations along the height as well as the horizontal direction were observed in the distribution of the vertical component w', calculated from airplane data.

Simultaneous measurements of the wind velocity fluctuations u' and w' conducted during ascents of the captive balloon made it possible to calculate σ_u and σ_w, which in turn were used further to calculate the kinetic energy of turbulent fluctuations E.

Figure 1 shows some characteristics of the daily variation of the quantities $\frac{\sigma_u}{\bar{u}}$ H $\frac{\sigma_w}{\bar{u}}$, characterizing the intensity of turbulent energy in the 10-300 m layer.

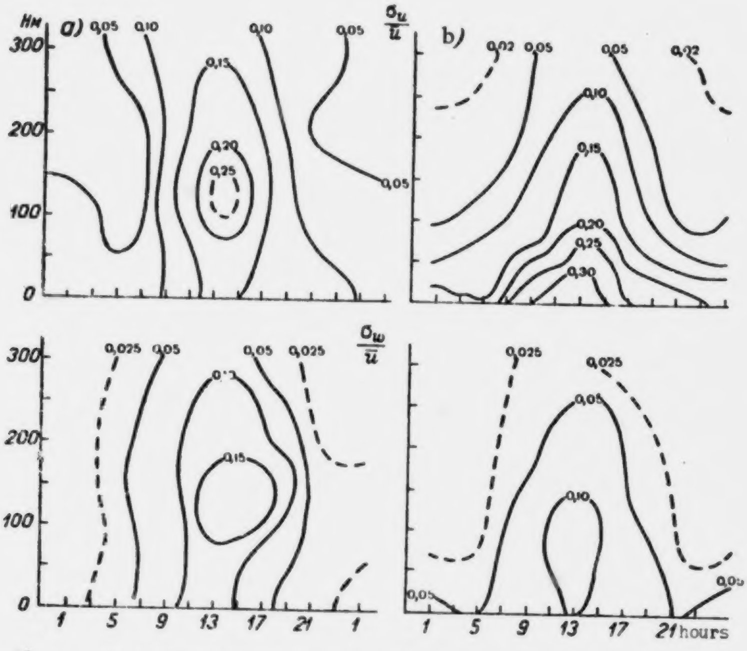

Fig. 1. Daily variation of the intensity of turbulent fluctuations in the 10-300 m layer for the longitudinal $\left(\frac{\sigma_u}{\bar{u}}\right)$ and vertical $\left(\frac{\sigma_w}{\bar{u}}\right)$ components during the warm (a) and cold (b) periods.

It is evident that the largest contribution to the energy balance is made by the term $\frac{\sigma_u}{u}$. Its absolute values are always greater than the terms $\frac{\sigma_w}{u}$. Both terms have a maximum during midday hours, in the warm period at a level $\approx$ 100 m, and in the cold period near the ground. As the wind velocity increases, $\frac{\sigma_u}{u}$ increases slightly, as indicated by data for the cold period. Particularly low values of both terms are observed in the nighttime in the presence of an inversion state. Mean values of $\frac{\sigma_w}{u}$ at low levels range from 0.1 to 0.4 and decrease rapidly with height.

It should be noted that the calculations of σ_u and σ_w included measurements and wind speeds from 2 to 12 m/sec for $u' \geqslant 0.1$ m/sec and a cloud height above 700-800 m.

Figure 2 shows the daily variation of the kinetic energy of turbulent fluctuations (in m^2/sec^2) calculated from the formula $E = \frac{1}{2}\sigma_w^2 + \sigma_u^2$. It is evident that the maximum of E occurs during midday hours in both periods of the year, the values of E during the warm period being almost 50% greater than during the cold period, and extending over a thicker layer. Frequently, in the calculations, the atmosphere is assumed to be isotropic. In this case, $\sigma_u=\sigma_v=\sigma_w$. Our comparison of σ_u and σ_w showed that the ratio $\frac{\sigma_w}{\sigma_u}$ depends substantially on the Ri number. When Ri=2, this ratio is approximately 0.3, and when Ri=-0.5, it increases to 0.7-0.8. In the presence of a marked instability, occasionally $\sigma_w > \sigma_u$. In general, as the instability increases (Ri decreases), both the absolute value of σ_w and the ratio $\frac{\sigma_w}{\sigma_u}$ increases.

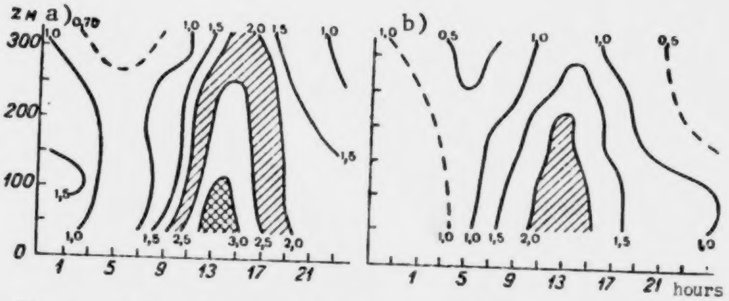

Fig. 2. Daily variation of the kinetic energy of turbulent fluctuations E m^2/sec^2 during the warm (a) and cold (b) periods.

By determining the vertical gradients of temperature γ_o and wind β from the observed vertical profiles of temperature and wind, and having calculated k and E, one can calculate all the components of the turbulent energy balance equation. Here it is necessary only to consider certain characteristics of the calculation of the term A. Not only the magnitude of this term, but in many cases its sign as well depend on the assumed equilibrium temperature gradient γ_e. It is assumed that γ_e=0.6°/100 m, but Budyko and Yudin [2] recommend that this value be taken as approximately 0.6°/100 m. In this connection, we made a preliminary calculation of the term A and of the sum of all the terms of the turbulent energy balance equation

$$\sum = k\beta^2 + k\frac{g(\gamma_0 - \gamma_e)}{T} + \frac{\partial}{\partial z} k \frac{\partial E}{\partial z} - \varepsilon - \frac{dE}{dt} \qquad (7)$$

in two variants: for γ_e=1°/100 m and γ_e=0.6°/100 m (Table 1). The calculation was based on data of balloon sounding at Voyeykovo.

Table 1

Mean Daily Values of A and Σ.

Season	H m	$\gamma_e = 1°$ 100 m		$\gamma_e = 0{,}6°/100$ m	
		A	Σ	A	Σ
Warm	100	−406	−398	−29	−21
	200	−197	−242	80	35
Cold	100	−496	−196	−309	−9
	200	−305	−321	−75	−91

According to Table 1, when γ_e=1°/100 m during the warm and cold periods in the layer up to 200 m, A has large negative values, which in any event is rather improbable for the warm period. Values of Σ are also obtained for which the turbulent energy balance equation does not close. If one assumes γ_e=0.6°/100 m, then during the warm period the values of A and Σ obtained are closer to the actual values. Negative values of A at the 100 m level during this period are explained by the presence of thick surface inversions, the dissipation of which requires considerable energy of turbulent fluctuations in the night hours.

During the cold period, A has a negative sign, indicating a stable state of the atmosphere and the necessity of a considerable expenditure of kinetic energy to develop turbulent motions. Analysis of the data of Table 1 indicates that in further calculations one can assume γ_e=0.6°/100 m.

The daily and annual variation of the components of the turbulent energy balance equation are given in Table 2, taken from [5]. The main source of supply of turbulent energy in the lower layers of the atmosphere is the transformation of the fundamental motion, which decreases sharply with height. If the amount of this energy at 100 m is taken as 100%, then during the warm period it will amount to only 30% at a height of 200 m and to 37% during the cold period and at a height of 300 m, to 10 and 9% respectively.

For the conditions that we assumed, the treatment included only cases with u$\geqslant$2.5 m/sec, and this obviously accounts for the fact that during the warm season, the largest values of $k\beta^2$ occur in the night hours, when the maximum of β is observed, despite the decrease in k. During the cold period, the maximum of $k\beta^2$ takes place during the midday hours. The inflow of energy of convective motions in the 300 m layer during the warm period will be positive ($A = 85$ cm^2/sec^3), i.e., the convection energy will promote the development of turbulence.

During the cold period, in the course of almost all days with the exception of midday hours, A has a negative sign, which promotes an attenuation of turbulence. The values of ε (dissipation rates) in the 100-300 m layer have a maximum at 100 m (no data are available near the earth's surface). In a stable state, ε undergoes relatively little change with height, whereas in an unstable state there takes place a comparatively rapid decrease of ε to the 300 m level. The total ε for 24 hours during the warm and cold periods of the year in the layer up to 300 m changes over comparatively narrow limits and depends more on the intensity of wind gusts, primarily on σ_u.

The diffusion transport of turbulent energy D is directed from the ground to the upper layers in both periods; in the warm period, D in the 0-100 m layer is almost 3 times as large as in the cold season, and at the 200 m level the diffusion transport is practically nil. The term dE/dt is determined as the difference of relatively large values of kinetic energy, and is very small at all times. Obviously, in the layer up to 300 m, one can practically assume that $\frac{dE}{dt} \approx 0$; this term may be neglected in the equation, and the process itself may be considered quasi-stationary.

Table 2 also gives values of Σ characterizing the conditions of closure of the turbulent energy balance equation. We see that the mean daily values of Σ are comparatively small in both periods of the year; Σ is positive in the daytime and negative at night. The cited data on the calculation of the turbulent energy balance make it possible to explain, albeit in a somewhat simplified form, the contribution of each term to the turbulence process and, hence, to the conditions of diffusion of impurities.

Table 2

Daily and Annual Variation of Components of the Turbulent Energy Balance (cm^2/sec^3) at Voyeykovo (for $u' \geq 0.1$ m/sec).

Time, hours	H m	Warm Period						Cold Period					
		$K\beta^2$	A	D	ε	$\frac{dE}{dt}$	Σ	$K\beta^2$	A	D	ε	$\frac{dE}{dt}$	Σ
1	100	143	−83	−28	88	−1	−55	76	−70	5	46	0	−45
	200	24	−17	9	29	0	−13	18	−20	1	38	0	−39
	300	6	−3	—	21	0	—	5	−11	—	32	0	—
5	100	123	−110	−2	27	0	−16	100	−114	7	15	0	−22
	200	33	−61	−7	34	0	−69	44	−54	1	14	0	−23
	300	10	−32	—	23	0	—	13	−17	—	10	0	—
9	100	93	41	−25	18	1	90	95	−43	−17	64	0	−29
	200	53	38	2	18	0	75	64	−35	−3	58	1	−33
	300	15	12	—	14	0	—	16	−26	—	28	0	—
13	100	58	181	−123	74	1	41	175	0	−42	96	1	36
	200	12	100	18	48	1	81	71	75	−2	87	1	56
	300	10	49	—	43	1	—	14	20	—	69	1	—
17	100	38	32	−35	28	−1	8	172	−7	−27	51	1	88
	200	28	46	−15	30	−1	30	54	−21	6	32	−1	8
	300	16	16	—	24	−1	—	10	−24	—	18	−1	—
21	100	117	−90	−21	95	0	−89	102	−75	−4	60	0	37
	200	25	−26	2	70	0	−69	17	−20	−3	55	0	−61
	300	2	−8	—	60	0	—	4	−10	—	31	0	—
Daily Mean	100	572	−29	−234	330	0	−21	720	−309	−88	332	0	−9
	200	175	80	9	229	0	35	268	−75	0	284	0	−91
	300	50	34	—	185	0	—	62	−108	—	188	—	—
Mean in Layer	100—300	806	85	—	744	—	—	1050	−492	—	80[illegible]	—	—

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I. V. VASILCHENKO, P. A. VORONTSOV

THE TURBULENCE IN THE LOWER 500m ATMOSPHERIC LAYER AND POLLUTANT DIFFUSION*

The results of atmospheric turbulence investigation in the lower 500m layer received with the help of balloon, helicopter and aircraft soundings are stated. The instruments were used allowing to measure temperature and air humidity, atmospheric pressure, wind velocity and its longitudinal and vertical pulsations, and also overloads experienced by aircraft or helicopter at different levels over the underlying surface. It is shown that the complex of characteristics received in such a way allows to make calculation of some quantities which characterize air flow structure and turbulence intensity and compute the components of turbulent energy balance equation. The main regularities of spatial-temporal distribution of turbulent intensity, kinetic energy of turbulent pulsations and turbulent coefficient, and also the principal peculiarities of diurnal course of turbulence energy balance equation components are given for warm and cold periods of the year in the lower layer up to 300m. The turbulence intensity maximum is observed in the day-time in warm period at the level of ≈100m and in the cold period near the underlying surface. The kinetic energy of turbulent pulsations is decreasing with height and has a maximum

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* Editor's note: The abstract is presented as given in English with the original Russian article.

in the diurnal course in the day-time. The presence of maximum at neutral and unstable stratification at the level of 100—200m is characteristic for the vertical profile of turbulent coefficient. The substantial decrease of turbulence coefficient value and its slight change with height in the layer of 100—200m is observed under stable stratification. The turbulence coefficient value depends, on the whole, on wind velocity, thermodynamical stratification, roughness of underlying surface, terrain orography and averaging period.

The main source of turbulence energy in the lower atmospheric layer is the energy transformation of principal motion, the value of which sharply decreases with height and compiles about 30 and 10%, respectively, at the level of 200—300m from its value at the height of 100m. The buoyancy force in the warm period of the year is an additional source of turbulent energy and acts in reverse direction in the cold period, except for the day-time. The value of dissipation of turbulent energy decreases rather quickly with height under unstable condition and changes little under stable stratification. The diffusive transfer of turbulent energy is directed from the underlying surface to the upper layers in both periods of the year, this value in the warm period being three times greater than in the cold one. The value of kinetic energy variation of turbulent pulsations with time in all the periods is very small in comparison with other members of turbulent energy balance equation.

ATMOSPHERIC TURBULENCE AT SMALL HEIGHTS

N. Z. Pinus (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 109-129, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

In recent years, considerable attention has been devoted to the study of turbulence in the planetary boundary layer. These studies are of major scientific and applied importance, particularly for meteorological aspects of atmospheric pollution in connection with the steadily increasing emission of noxious substances by industrial enterprises, motor transport, etc. Knowledge of the characteristics of turbulent behavior in the atmospheric boundary layer is essential for working out the physical principles and economical methods of control of noxious atmospheric pollutants. In any method of purification of industrial emissions that are harmful to human health, part of them remain in the surface and boundary layers of the atmosphere. An attenuation of the harmful effect of even the residues of these emissions substantially depends on the direction of the air currents, and on the degree and character of turbulent diffusion of air penetrated by the noxious impurities.

To date, a number of significant theoretical studies have been carried out pertaining to turbulent behavior in a thermally stratified atmospheric boundary layer [9, 13, 21]. Because of technical and operational difficulties, the physical characteristics of the turbulent behavior of the atmospheric boundary layer have been studied much less closely, particularly under diverse natural conditions. Furthermore, it has not been possible thus far to standardize the terminology, the definition of the constants, and the units of measurement, so that the results of experiments performed by different scientists still cannot always be compared.

In this paper, we will discuss the results of experimental studies of turbulence conducted at the Central Aerological Observatory. Although these studies initially were not connected with atmospheric pollution problems, in our view some of the aspects of turbulence at low height presented below will be helpful in providing a better physical picture of the actual conditions of turbulization of the planetary boundary layer. Moreover, they will provide an opportunity for the development of methods of taking these conditions into account in the elaboration of measures aimed at the control of noxious atmospheric pollutants.

Some General Characteristics of Turbulence at Small Heights

As we know, turbulence is one of the characteristic properties of atmospheric air currents. At low heights, it depends on many factors: height above ground, degree of hilliness, character and thermophysical properties of the underlying surface, thermal stratification, wind velocity, and vertical gradient of wind velocity. A daily variation of turbulence with maximum intensity (above dry land) in the midday hours is observed in the boundary layer of air. For a quantitative evaluation of the integral turbulence intensity, the following ratio is used:

$$\psi=\frac{\sigma_u}{\bar{u}}, \tag{1}$$

where $\bar{u}$ is the mean flow velocity, and σ_u is the root-mean-square value of the fluctuation velocity $u' = u - \bar{u}$.

Experimental studies with the aid of airplanes, captive balloons, and radar stations have shown that the integral turbulence intensity near a level and flat earth's surface for an indifferent thermal stratification is equal to an average of 0.1; for a stable stratification, to about 0.3, and for an unstable stratification, to 0.3 or more.

Studies have shown [8] that it is very significant that the distribution of σ_u^2 can be described with an adequate approximation by the normal law of distribution of random values.

On the average, the integral turbulence intensity decreases as the distance from the earth's surface increases. Radar and balloon observation made it possible to determine the dependence on height. Although in each specific case the vertical profile of ψ has a complex stratified character related to the characteristics of the vertical temperature profiles and mean wind velocity, on the average, a decrease of ψ with height is observed. An idea of these variations can be obtained from Table 1, which gives data of observations from captive balloons.

Table 1

Dependence of Integral Turbulence Intensity on Height

Quantity	Height, m						
	100—500	500—1000	1000—1500	1500—2000	2000—2500	2500—3500	3500—4500
σ_u cm/sec	99	53	86	55	63	47	43
ψ %	9,6	5,9	9,2	4,5	5,5	3,2	2,8

The decrease in turbulence intensity with height is inversely proportional to approximately the square root of the height [5, 8]. In different applied problems, the relationship between ψ and the mean wind velocity can be used for an approximate evaluation of the fluctuations of the wind velocity u' from measurements of the mean wind velocity.

According to the data of radar measurements [5, 12, 21], at small heights, the fluctuations of the longitudinal component of the wind velocity are usually greater than the fluctuations of the transverse component (in the horizontal plane), and their ratio may exceed 1.3.

Above, we dealt with characteristics of fluctuations of the horizontal component of the wind velocity. The measurement of the vertical component of the wind velocity presents exceptional operational and instrumental difficulties [1]. The largest amount of data on fluctuations of the vertical component of the wind velocity was collected at the Central Aerological Observatory from numerous measurements during flights with free balloons [11, 14]. The velocity averaged over 6-10 sec was arbitrarily taken as a single measurement.

The studies showed that in cloudless weather (or outside clouds), the distribution of the velocity of vertical motions w with height is usually stratified in character. Moreover, the mean velocities of ascending motions $\overline{\omega}_+$, are not always equal to the mean velocities of descending motions $\overline{\omega}_-$. In many flights, the intensification or weakening of vertical motions is flarelike in character. At times, large values of ascending and descending motions were observed when the velocities reached 2-3 m/sec.

On the other hand, the velocities were below the initial sensitivity of the measuring instruments (~1 cm/sec) for a long period of time. The variation in velocity and change of sign (of the direction) were disordered in character, but sometimes also periodic. Analysis of the measurements also showed that high velocities of vertical motion keep their sign longer. Table 2 lists data on mean velocities of ascending and descending vertical motions, obtained from a long series of flights (38) of free balloons.

Table 2

Distribution of the Velocity of Vertical Motions of Air with Height

Height, M	$\overline{w}_+$ cm/sec	$\overline{w}_-$ cm/sec	$\frac{\overline{w}_+}{\overline{w}_-}$	σ_w cm/sec
200--600	49,3	22,2	2,22	45,0
600--1200	25,4	22,0	1,15	29,6
1200--1600	24,0	24,0	1,00	31,0
1600--2000	36,3	36,0	1,00	45,1
2000--2500	27,5	35,5	0,78	40,0
2500--3000	26,0	27,0	0,96	33,1

As is evident from Table 2, on the average, $\overline{w_+} > \overline{w_-}$ in the atmospheric boundary layer in cloudless weather. This difference is particularly clear-cut in the atmospheric layer up to a height of 500-600 m above the earth's surface.

Comparison of the data of Tables 1 and 2 shows that on the average, $\overline{\sigma_u} > \sigma_w$ in the lower troposphere, particularly at small heights.

For technical reasons, balloon observation did not permit a detailed study of the characteristics of the fluctuations of wind velocity components at heights below 200 m. Some idea of these characteristics is given by airplane data, listed in Table 3. They were obtained by Burns [23] in the course of three flying experiments conducted in a "Canberra" airplane. During the first two experiments, the vertical temperature gradient was 1.05°/100 m, and during the third flight, 1.11°/100 m. The wind velocity near the ground was respectively about 6 and 3 m/sec, and the vertical gradient of the mean wind velocity was substantially less than 1 m/sec per 100 m of height.

Table 3

Dependence of $\frac{\sigma_w}{\sigma_u}$ on Height

Height, m	σ_w/σ_u			σ_w m/sec
	1	2	3	
30	—	—	0,90	
60	0,99	0,73	1,29	0,96 (14)
150	1,23	1,08	1,33	1,19 (7)
300	1,20	1,46	—	1,05 (4)

For the stated conditions, the relationship between σ_w and σ_u at small heights has a characteristic vertical profile: up to heights of 50-70 m, $\sigma_w < \sigma_u$, and at greater heights, $\sigma_w > \sigma_u$. This indicates a substantial dependence of the scale of fluctuations of the vertical wind velocity component on the height above the earth's surface. The last column of this table gives root-mean-square values of σ_w, and the number of measurements is indicated in parentheses.

To conclude this section, let us note that in addition to motions of purely turbulent character, more or less ordered ascending and descending motions may be observed in the atmosphere at small heights, particularly in the daylight hours and over surface portions with markedly different thermophysical properties. These motions have been dealt with in very interesting experimental studies made at the Main Geophysical Observatory. Results of these studies have been published recently in a comprehensive monograph by P. A. Verontsov [3].

Structure of the Turbulent Atmospheric Boundary Layer

Balloon and airplane studies of turbulence in the clear sky have shown that vast zones of intense turbulence are rarely encountered in the atmospheric boundary layer [15]. Moreover, the filling of the space of the boundary layer with turbulent disturbances is not continuous, but localized, and the zones of turbulence move along with the mean flow. Under the influence of the characteristics of the underlying surface and of the thermal and dynamic behavior in the boundary layer, localized zones are usually formed in the boundary layer in the form of "bursts". Such bursts of turbulence may assume a high frequency, increase in size as they develop, and merge with one another as they move along the current. Thus, turbulent zones in the form of spots are formed along the current.

The alternation of quasi-laminar and turbulent flow regimes is observed in a turbulized boundary layer. At a fixed point of space above which an air flow is moving, the quasi-laminar regime naturally predominates in time at the start of the process of boundary-layer turbulization, and, as turbulence develops, the turbulent regime becomes predominant. The relationship between the time of predominance of the quasi-laminar regime and that of the turbulent regime depends (other things being equal) on the height above the earth's surface. With height, there takes place a shift in the time of start of turbulization and onset of fully developed turbulent regime. Thus, an intermittence of turbulence may be observed during a considerable part of the time within the atmospheric boundary layer.

As was shown by our experimental studies [15], such a regime is also observed in the stage of turbulence damping. It follows from these studies that the damping does not occur simultaneously in the entire turbulized layer, so that a stratification of turbulence in height is formed with regimes differing in turbulence intensity and degree of intermittence.

The intermittence of turbulence is also observed in the transition zone between the turbulized zone and the undisturbed part of the atmosphere located above it. The causes and mechanism of formation of intermittence within a turbulized atmospheric boundary layer differ fundamentally from the cause and mechanism of formation of intermittence at the upper boundary of the turbulized layer. In the first case, as already noted, the intermittence is caused by the initiation (or damping), spontaneous and localized in time and space, of a turbulent regime. In the second case, the initiation of intermittence is due to the characteristics of penetration of flow velocity fluctuation from the turbulized region into the outer quasi-laminar region.

Experimental studies have shown [18] that even in the free atmosphere, turbulent layers have fairly distinct boundaries outside which there is no turbulence. However, as a rule, the boundary between the turbulized and laminar portions of the air flow has irregular outlines in the form of bulges that alternate in a disordered manner in time and space. The change in the height of the bulges (along and across the flow) and their structure are statistical in character. The phenomenon described is explained by the fact that air can enter freely from the quasi-laminar region into the turbulent region, whereas turbulent fluctuations can penetrate into the quasi-laminar region of flow only after being substantially weakened during their penetration.

According to Landau and Lifshits [10], the damping of the amplitude of velocity fluctuations upon penetration into a laminar (quasi-laminar) region of flow can be described to a first approximation by the formula

$$A_H = A_0 e^{-\Omega H}, \qquad (2)$$

where A_0 is the initial amplitude of the fluctuation velocity, Ω is a wave number inversely proportional to the spatial scale of turbulent fluctuations, and H is the coordinate along the normal to the turbulized layer.

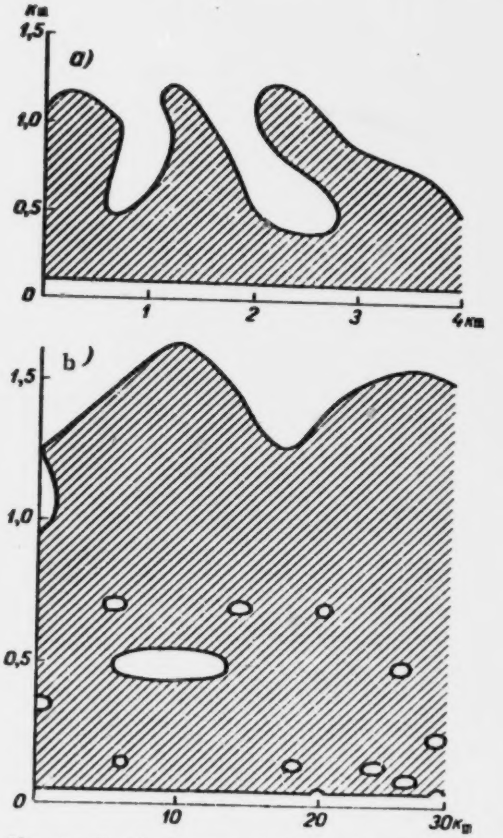

Fig. 1. Vertical cross sections of turbulent atmospheric boundary layer based on data of PO-2 airplane (a) and atmospheric layer with unstable thermal stratification based on data of LI-2 airplane (b).

It follows from (2) that the smaller the scale (the larger the wave number) of turbulent fluctuations, the smaller the distance from the turbulized layer at which they damp out. Hence, turbulent fluctuations that can penetrate far into the quasi-laminar region of flow can be only comparatively large-scale fluctuations propagating from the so-called mother turbulent layer. They are the ones that produce the irregular distortions of the turbulized layer boundary and the alternation of turbulent and quasi-laminar flow regimes. As an example, Fig. 1 shows two vertical cross sections of turbulized atmospheric boundary layers. The cross sections were plotted by pasting together [18] data of measurements of airplane overloads carried out during flights over flat terrain.

The degree of intermittence is estimated from the value of the intermittence coefficient α, equal to the ratio of the combined horizontal extent of the turbulized portions of the flow to the total length of the flow intersected by the airplane in a horizontal flight or taking place at a given level through a given point of space. Obviously, the vertical profile of α depends on the factors leading to turbulization of the air flow, and in the boundary layer, in addition, on the distance from the earth's surface.

As an example, Fig. 2 illustrates three generally fairly typical vertical profiles of α. The first type 1) corresponds to conditions of

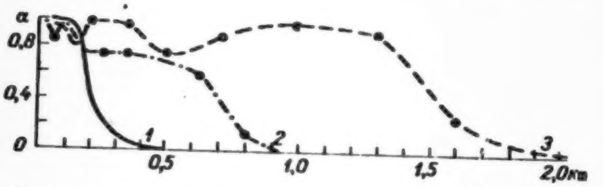

Fig. 2. Vertical profiles of the coefficient of intermittance of turbulence.

a surface temperature inversion breaking down in the morning hours, the second 2) to conditions of slight temperature lapse rates but large lapse rates of the mean wind velocity, and the third 3), to conditions of developed convection. Comparison of these profiles shows that the vertical distributions of α in the zone of the upper part of turbulized layers are completely similar, and can be described by the normal distribution law. From a physical standpoint, such a distribution is a consequence of the statistical character of the variations of the height of the bulges and of the order in which they succeed one another. Quantitative characteristics of these properties of boundary layers are illustrated in Table 4. From these examples it is evident that in boundary layers, the atmospheric layer depth in which an intermittent turbulence is observed is caused by the damping of relatively small-scale fluctuations penetrating into the quasi-laminar part of the flow, may reach one-half the thickness of the mother layer, i.e., main part of the turbulized boundary layer, and under certain conditions, exceed it severalfold.

Table 4

Parameters of Turbulized Boundary Layers

Profile	Thickness of Layers, m		
	Boundary Layer	Mother Layer	Intermittant Part
1	600	100	500
2	1000	650	350
3	2000	1300	700

Furthermore, on analyzing curves 2 and 3 of Fig. 2, we see that the significant lapse rates of the mean wind velocity and particularly of the air temperature lead to an increase in the thickness of the turbulized boundary layer and cause discontinuities in the vertical profile of α, producing and intensifying the intermittence within the boundary layer. Considering the statistical nature of turbulence intermittence, one can expect that in these cases (for the second and third types of α profiles), fluctuations and concentrations of the impurities carried by the turbulized flow should be observed. In general, it may be postulated that the intermittence of turbulence (allowing for the boundary layer thickness) should have a certain effect on the character, degree of continuity and height of dispersion of impurities discharged by industrial enterprises over a given geographical point.

Coefficient of Turbulent Exchange in the Boundary Layer

In theoretical studies of the boundary layer, an essential factor is the character of vertical profiles of the vertical component of the exchange coefficient k. Unfortunately, there is as yet no generally accepted and standardized formula for calculating the turbulence coefficient, and hence, no sufficiently reliable procedure for measuring the atmospheric parameters necessary for the calculations of k. Even more complicated is the problem of determination of horizontal components of the turbulent coefficient, knowledge of which is essential in many applied problems, including the study of diffusive transport of different kinds of pollutants.

Data have been accumulated at the Central Aerological Observatory on the coefficient of vertical turbulent exchange. The initial data used were measurements of fluctuations of the vertical component of the wind velocity in airplane and free balloon flights [11, 14, 16].

Calculations based on measurement data from free balloons were carried out by using the formula

$$k = \frac{\pi}{4} \frac{\Delta t}{n} |\overline{w'}|^2, \tag{3}$$

where $w' = w - \overline{w}$ stands for the fluctuation velocity of vertical motions, i.e., the deviation of the velocity from the mean; Δt is the time interval for which the measurements are made; n is the number of changes of sign (direction) of the velocity during the time interval Δt.

Using the airplane data, the calculations of the coefficient of vertical turbulent exchange were carried out with the aid of the structural-kinematic formula of Lyapin, refined by Dubov [6] and German [4]:

$$k = \frac{b \bar{\tau} |\overline{\Delta n}|}{2\delta\eta}, \tag{4}$$

where $|\overline{\Delta n}|$ — is the mean absolute increment of vertical overload of the airplane (in units of gravitational acceleration g); $\bar{\tau}$ is the mean time of retention of the sign (direction) of the overload; $\delta = \frac{\rho_z}{\rho_0}$ is the ratio of the density of air at the flight altitude (ρ_z) to its density on the earth's surface (ρ_0); b is a coefficient dependent on the technical flight data and flight speed of the airplane; η is a factor considering the transfer function for disturbances of different frequencies acting on the airplane.

The values of k obtained from the airplane measurement data were, as a rule, greater than those calculated from free balloon measurements. This was because the initial sensitivity of the system balloon-instrument was greater than that of the system airplane-instrument. Although the measurements were made in PO-2, LI-2 or IL-14 airplanes, for which the initial sensitivity (based on the overload increment) to vertical wind velocity fluctuations is comparatively high (for airplanes), the turbulence coefficient was obtained for conditions when bumping of the airplane was observed, i.e., conditions that were already more or less strongly turbulent.

If the turbulence intensity is evaluated from the magnitude of the turbulence coefficient, then, as was shown by experimental studies [16], the spatial distribution of this parameter of atmospheric turbulence is very complex in character. The field of the turbulent exchange coefficient is not uniform and consists of local foci (nuclei) of intensified turbulence, next to which there are zones of weak turbulence. The size of such foci ranges from 50-100 to 300-500 m in the vertical direction and from 1-2 to 4-5 km in the horizontal direction.

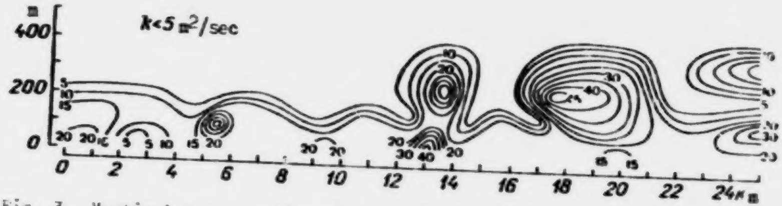

Fig. 3. Vertical cross section of atmospheric turbulence field, 21 April 1962.

Vertical cross sections of the turbulence coefficient field permit one to draw a conclusion with regard to the mechanism of propagation of turbulence along the height and to the characteristics of the focal structure of this field. Fig. 3 shows a vertical cross section of the field of atmospheric turbulence, plotted from data of measurements from LI-2 airplane made over flat terrain on 21 April 1962 between 8 and 11 A.M. The weather was clear. A temperature inversion was observed in the surface atmospheric layer until approximately 9:30 A.M., but by 11 A.M. the temperature gradients were already close to adiabatic.

Fig. 3 leads to the conclusion that the vertical propagation of turbulence does not take place in the entire space at once, but occurs as a result of the upward "breakthrough" of individual nuclei having a comparatively high turbulence intensity in them. Let us note that these nuclei, by penetrating to great heights into the quasi-laminar portion of the atmosphere, apparently can play here the role of so-called initial turbulence, which promotes a general development of turbulence at these higher levels. In addition, Fig. 3 gives an idea of the spatial distribution of the outer intermittence of turbulence in the turbulized atmospheric boundary layer in the stage of daily variation of turbulence development.

As an illustration, we give another cross section of the turbulence field (Fig. 4) for clear weather conditions and fairly appreciable vertical temperature gradients in the layer up to a height of about 1200 m.

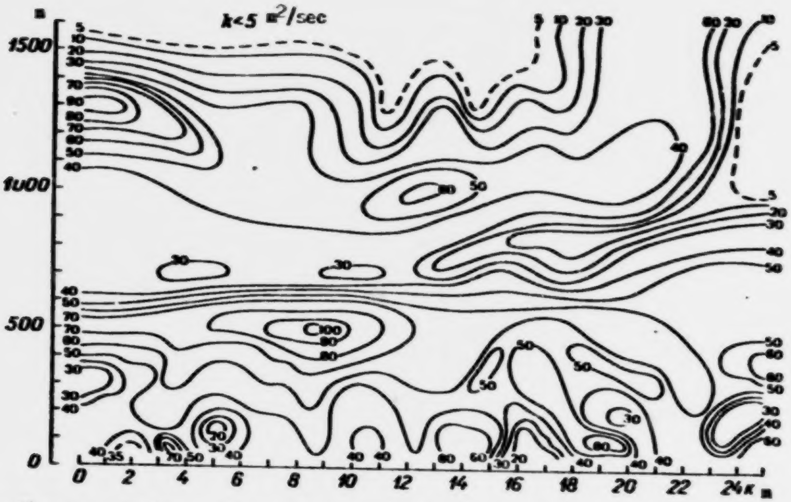

Fig. 4. Vertical cross section of a field of atmospheric turbulence, 20 April 1962

A "joining" and "interaction" of an ordinary turbulized boundary layer with a turbulized layer of generally thermal origin were observed in this experiment. The horizontal distribution at heights of 600-700 m is fairly uniform. The main point, however, is that the vertical profiles of k over different parts of the region where the flights were made differ substantially from one another. This is evident from Fig. 5, which shows the turbulence coefficient profiles taken from Fig. 4 for distances of 5, 9 and 19 km from the origin of the "platform" over which the flight experiment was conducted. Particularly great are the differences in the layer up to a height of 400-500 m. The localizability (in time and space) of the vertical profiles of k naturally complicates the selection of an approximation of the k profile that would most closely reflect, in theoretical calculations, the turbulent regime of the atmospheric boundary layer for specific applied cases.

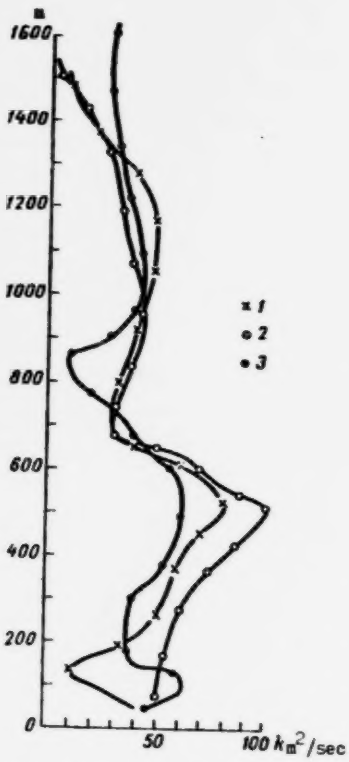

Fig. 5. Vertical profiles of turbulence coefficient at different distances from origin of platform, 20 April 1962.

1) 5 km, 2) 9 km, 3) 19 km.

Spectral Characteristics of Turbulence

Of particular interest is the question of the energy characteristics of a turbulent regime of motion. The first part of our report has already supplied some data on the values of ψ characterizing the integral turbulence intensity.

It is evident that the energy of turbulent motion $\sigma^2_{u,\,w}$ represents the sum of the energies associated with the turbulent eddies forming the spectrum of atmospheric turbulence.

Modern concepts of the turbulence spectrum consist in the following. Large-scale fluctuations draw energy from the destabilized fundamental flow. Being unstable, these fluctuations in turn successively "break-up" into finer fluctuations, down to a fluctuation of molecular character. At the same time, the kinetic turbulent energy is continually transferred from large eddies to small ones. This flow of energy in the turbulence spectrum is eventually dissipated, i.e., converted into heat, in the region of the smallest-scale eddies, where the influence of vixcosity is appreciable. In the atmosphere, where the influence of the force of gravity may be neglected (in the case of indifferent thermal stratification), the power spectrum of turbulence characterizing the scale distribution of turbulent energy consists of three parts: 1) a region of large (anisotropic) eddies, into which turbulent energy from the fundamental motion penetrates, along with energy from large eddies; 2) a region of dissipation of turbulent energy as a result of viscosity and 3) a transition range (so-called inertial range) in which the appearance and dissipation of turbulent energy are small compared with the inflow and expenditure of energy due to "cascade" energy transfer over the spectrum associated with the "break-up" of eddies.

According to the Kolmogorov-Obukhov theory of turbulence, the spectrum of wind velocity fluctuations in the inertial region (range) of the spectrum is described

$$s(\Omega) = c\varepsilon^{2/3}\Omega^{-5/3}, \tag{5}$$

where $s(\Omega)$ is the spectral density, ε is the mean rate of dissipation of the kinetic energy of turbulent motions, c is a universal constant equal to 0.45-0.50 (to within 20-15%) according to recent data if the wave number Ω is measured in radians per unit length.

Experimental studies in the lower half of the troposphere have shown that the fluctuation spectra depend on the thermal stratification of the atmosphere and nature of the boundaries of turbulized layers of the atmosphere [20]. Four basic types of spectra have been successfully separated (Fig. 6). The first type corresponds to conditions of indifferent thermal stratification of the atmosphere and is described by expression (5). The second type is observed in the presence of superadiabatic temperature lapse rates, when there is an inflow of energy on certain scales owing to thermal instability of the atmosphere. The "minus five-thirds" law corresponds to the left (low-frequency) and right (high-frequency) portions of the $s(\Omega)$ curve. However, the right part of the $s(\Omega)$ curve is located in the region of higher spectral densities. The third type of the $s(\Omega)$ curve corresponds

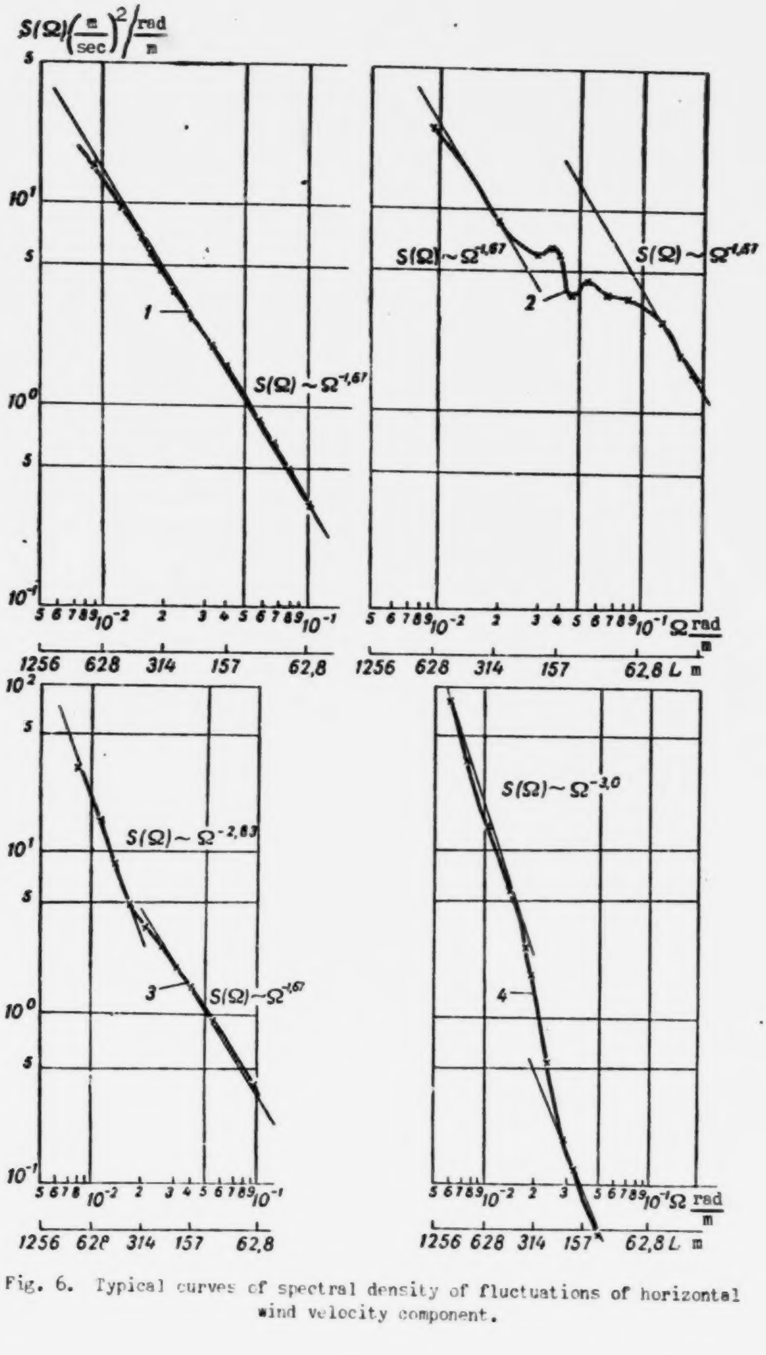

Fig. 6. Typical curves of spectral density of fluctuations of horizontal wind velocity component.

to stable conditions of thermal stratification. This curve may be approximated by two linear segments, which can be described by an exponential law. Up to scales of approximately 300 m, the absolute value of the exponent is 2.83, and for smaller scales, 1.67, and thus obeys the "minus five-thirds" law. Attention should be turned to another two important points: 1) the absolute value of the exponent in (5) for conditions of stable thermal stratification may vary over comparatively wide limits, from 2.0 to 3.5; 2) the increased value of the mean wind velocity lapse rate does not alter the character of the s(Ω) curve in a stably stratified atmosphere, but shifts it toward higher spectral densities.

Finally, the fourth type is characteristic of intermittent turbulence, observed in a layer of stable thermal stratification, where in addition there is a low spectral density of large-scale turbulence because of its rapid damping as the distance from the mother turbulent layer increases. The frequency of a given type of spectra is related to the frequency of the types of vertical profiles of air temperature in a specific geographical area.

Treating turbulent diffusion as a factor determining the mixing and character of dispersion of impurities in the atmosphere, one must first of all estimate what scales of the turbulence spectrum are defined by the indicated processes. This simultaneously defines the spectral turbulence intensity. In particular, the spectral values of $\sigma_u^2 = \overline{u'^2}$ may be obtained from the energy spectrum if the intervals of scales (frequencies) are given for which it is necessary to calculate the turbulence intensity, as for example,

$$\overline{u'^2_{\Omega_{1-2}}} = \int_{\Omega_1}^{\Omega_2} s(\Omega')\, d\Omega'. \tag{6}$$

Let us note that without knowing the interval of the scales for which the turbulence intensity is defined, one cannot compare intensity data obtained in different investigations.

A spectral structure is displayed not only by the energetics of turbulent motion, but also by the coefficient of turbulent diffusion. In the inertial range, the turbulence intensity is determined by the magnitude of the mean rate of dissipation of turbulent energy ε. On the basis of dimensional considerations, the relationship between the variance of the wind velocity fluctuation $\sigma^2(k, w)$, the turbulence coefficient k and ε may be described by the expressions

$$\sigma_u^2 = A k^{1/2} \varepsilon^{1/2}; \tag{7}$$

$$k = A_1 \frac{\sigma_u^4}{\varepsilon}. \tag{8}$$

to within the constant factor A.

It follows from (8) and (5) that for conditions of indifferent thermal stratification

$$k_\Omega = A_2 \frac{\sigma_*^4}{s^{3/2}(\Omega)} \Omega^{-5/2}. \tag{9}$$

Somewhat different will be the dependence of k_Ω for other conditions of thermal stratification of the atmosphere. In addition, it is also necessary to determine experimentally the value of the constant factor in expression (9).

Expression (9) enables one to determine the scale of disturbances which causes the change of the vertical profile of the integral value of the diffusion coefficient k. In particular, the curves of Figs. 6 and 7 give an idea of the turbulence scales as a result of which one can expect the greatest changes of the turbulent diffusion coefficient.

Sources of Energy of Intense Turbulence at Low Heights

Studies of the spectral characteristics of atmospheric turbulence are based on the ideas that the atmosphere is a dynamically unstable system and that periodic wave motions exist in it continually. If these motions in turn become unstable, motions of a turbulent character arise. Thus, turbulent motions are the result of so-called secondary dynamic instability of the atmosphere. Being hydrodynamically unstable, these motions in turn generate smaller-scale turbulent motions, the latter generate still smaller ones, and so on.

Furthermore, as was indicated above, studies of atmospheric turbulence are also based on the hypothesis of a cascade transfer of turbulent energy over the spectrum, i.e., from large-scale eddies, formed as a result of instability of the fundamental flow, to smaller-scale eddies down to the scale determined by the action of viscosity forces. Hence, an essential part is played by concepts of continuity of the spectrum of atmospheric turbulence. If in the real atmosphere the described mechanism of generation and development of turbulence were the only one, i.e., if large-scale processes were the only source of turbulence, then the form of the power spectrum would in all cases be such that $s(\Omega)$ in the inertial range would be described by the "minus five-thirds" law.

The spectral region adjacent to the inertial range on the side of low frequencies contains the major part of kinetic energy of turbulent motions. This portion of the spectrum contains an energy maximum, whose intensity decreases toward the region of zero frequencies. The spectral region adjacent to the inertial range on the side of high frequencies is directly related to the dissipation of turbulent energy as a result of viscosity.

Sources of turbulent energy may exist in the real atmosphere only for isolated and comparatively narrow portions of the spectrum of atmospheric turbulence. Such sources may be an unstable thermal stratification, local orography of the terrain, etc. A stable thermal stratification of the atmosphere may serve as a "sink" of turbulent energy. These sources and "sinks" are best manifested in the atmosphere at small heights. At the same time, the effect on the underlying surface, with which the input of energy into the small-scale region of the spectrum is associated, is a continually acting factor. This phenomenon should of course diminish with height. The presence of a maximum in the small-scale region of the spectrum for the surface atmospheric layer was established experimentally by Van der Hoven [24], and Kolesnikova and Monin [7]. The presence of this maximum and of the principal maximum in the low-frequency portion of the spectrum to the left of the inertial range naturally leads to the formation of an energy minimum in the mesometeorological portion and left side of the micrometeorological portion of the power spectrum.

In 1966-67, two series of experiments (summer and winter) were carried out by the Central Aerological Observatory in the area of Khar'kov [2]. Each series lasted one month (July and January), during which radiosondes were released at an increased frequency (every two hours). In the same area and at the same time, flights were made in an IL-18 laboratory airplane equipped with a Doppler navigation system, a hot-wire anemometer, and other scientific instruments. Each month, 8-10 flights were made in the IL-18 (2-3 flights a week). The flights were made over horizontal platforms 200-250 km long at altitudes from 1 to 10 km. The chief purpose of this major experiment was to obtain data on wind velocity fluctuations which would permit the plotting of the power spectrum for a wide range of scales of turbulent motion. Wind velocity fluctuations in the range of scales from several hundred meters to several thousand kilometers were successfully studied up to a height of 10-11 km. The procedure for calculating $s(\Omega)$ functions is described in [17, 19].

Fig. 7 shows experimental spectra of fluctuations of the horizontal wind velocity component for July 1966 (a) and January 1967 (b). The power spectra are given only for heights of 1, 2, 3 and 5 km. Spectra for greater heights, obtained from data of experiments in the area of Khar'kov, can be found in [2].

Adhering to the hypothesis that the energy of macroturbulent motions in the process of "cascade break-up" of eddies is transferred to eddies of smaller size, and extrapolating the empirical functions of spectral density $s(\Omega)$, obtained for large-scale turbulence, into the region of large Ω values, i.e., into the mesoscale portion or even into the shortwave portion of the spectrum, one can estimate the value of $s(\Omega)$, caused by the presence of large-scale turbulence in the atmosphere for each of the indicated portions of the spectrum. Changes in the character of the various parts of such a spectrum should be explained as being due to external (additional) sources ("sinks") of turbulent energy. An inspection of Fig. 7 shows that in summer, at small heights (1-3 km), the $s(\Omega)$ values for the region of wave numbers $\Omega = 10^{-1}$-10^{0} rad/km

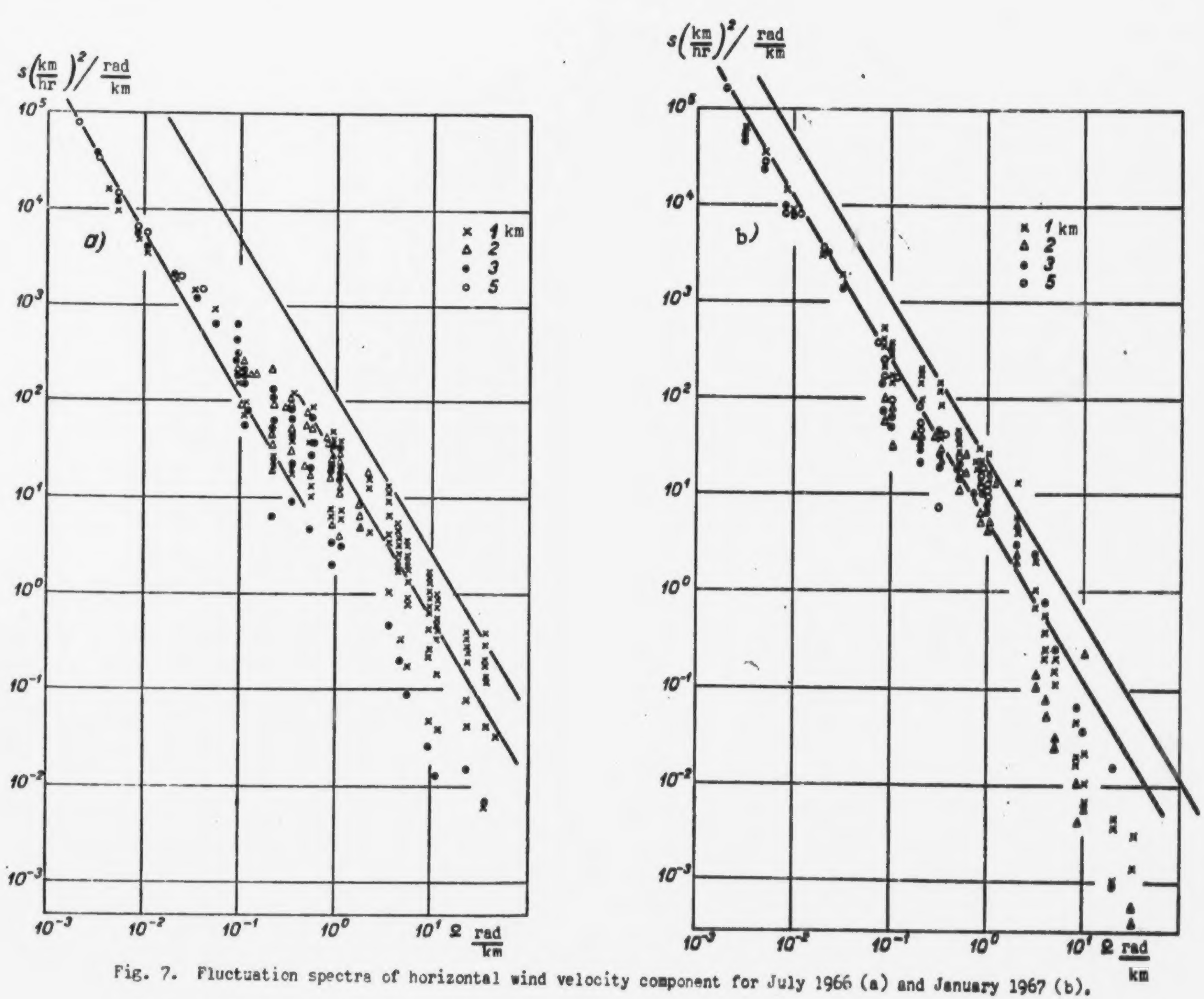

Fig. 7. Fluctuation spectra of horizontal wind velocity component for July 1966 (a) and January 1967 (b).

are much greater than the $s(\Omega)$ that would be expected if the chief source of energy for the indicated region of wave numbers were the energy of macroturbulent motions which flows into the mesocale region in the course of decay of macroturbulent motions and "cascade" energy transfer over the spectrum.

Large values of $s(\Omega)$ of mesoscale turbulence are due to the inflow of energy, apparently as a result of some processes of mesometeorological scale. Since the flight experiments were conducted over a flat terrain, it may be assumed that the source providing an additional flow of energy into the wave number range of 10^{-1}–10^{0} rad/km could have been the processes of formation and decay of mesoscale gravitational waves. Also appreciable was found to be the influx of turbulent energy at a height of 1 km into the region of wave numbers of 5×10^{0}–2×10^{1} rad/km as a result of an increased "cascade" input of turbulent energy from mesoscale turbulence, and also as a result of the thermal instability that was shown by measurements to take place in the boundary atmospheric layer reaching a height of 1.0-1.5 km.

As is evident from Fig. 8*, in winter, the energy input into the mesoscale region as a result of mesoscale processes was comparatively insignificant. In the microscale region ($\Omega \gg 5 \times 10^{0}$ rad/km), there was observed a considerable turbulent energy "sink" that should be explained by the influence of the negative buoyancy forces characteristic of stable thermal stratification conditions [22].

Unfortunately, under the conditions of the flight experiment, no data could be obtained on fluctuations of the horizontal component of the wind velocity in the atmospheric boundary layer for the scale region $\Omega > 10^{-1}$ rad/km, and no explanation could be given for the change in the character of the energy spectrum as the distance from the earth's surface increases (within the turbulized boundary layer). In any event, it may be stated with a fair degree of confidence that in analyzing the conditions of turbulization of the airflow at small heights, one should consider not only the local meteorological characteristics of the area, but also the characteristics of the mesoscale processes determining the weather of the area.

The complexity of the physical picture and mechanisms of turbulization of the atmosphere at small heights make the prediction of vertical motions and turbulence in the lower atmospheric layer difficult. This has been known for a long time, particularly to aviation experts. For this reason, many countries, while pursuing research on the development of turbulence prediction methods, are conducting laboratory simulation and research on full-scale models of flow around the approaches to landing strips of airports located near mountains, hills, and high installations, for the purpose of working out recommendations for pilots on the paths and ways of approaching runways so that the landing can take place under the most favorable conditions. In addition, long (2-3 years) before the start of construction of new airports, detailed studies are organized to determine the meteorological conditions in the boundary atmospheric layer in the area of the planned airport. Multichannel telescopic masts carry meteorological instruments for high-precision measurements of fluctuations of wind velocity and direction, temperature fluctuations and vertical gradients of the mean wind velocity and temperature, allowing for the prevailing directions of air currents, etc. Results of these measurements are considered in generalized form in the final design of airports and are included in the navigation instructions of the airport. This experience should be utilized in work connected with the calculation and control of atmospheric pollution.

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* Editor's note: No Fig. 8 accompanies this paper. A reference to Fig. 7 is probably intended.

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N. Z. PINUS

ON ATMOSPHERIC TURBULENCE AT LOW LEVELS*

The turbulence at low levels depends on the height over the earth surface, the relief, the character and thermophysical features of underlying surface, the thermal air stratification, and the vertical distribution of wind velocity. The daily course of turbulence with maximum intensity (over the land) is observed in the boundary air layer during the day time.

Experimental investigations carried out with the help of aircrafts, captive balloons, and radars showed that turbulence intensity defined as the ratio of mean square deviation to the mean flow rate is equal, on the average, to 0.1 under indifferent thermal stratification near the ground surface, to 0.03 under stable stratification, and 0.3 or more under unstable stratification. At a sufficient removal from the underlying surface the decrease of turbulence intensity with height is marked which is inversely proportional to approximately square root of the height. According to radar measurement data, pulsations of longitudinal component of wind velocity at low levels are usually greater than pulsations of cross component, and their ratio reaches 1.3 and more.

Experimental investigation shows that spatial distribution of the turbulence as estimated from the turbulence coefficient has quite a complex character. The field of exchange coefficient is not uniform and consists of local centres (nuclei) with increased turbulence close to which zones with weak turbulence are situated. The size of such centres changes from 50—100m along the vertical and 1—2km along the horizontal up to 300—500m along the vertical and 4—5km along the horizontal.

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* Editor's note: The abstract is presented as given in English with the original Russian article but has been slightly edited.

Sometimes the layers with rather clear-cut boundaries are observed, outside which the turbulence is practically absent. The boundary between turbulized and laminar (quasilaminar) parts of air flow has irregular contours which change in time and space randomly. Turbulent pulsations can penetrate in laminar region only with significant weakening along their penetration way. The attenuation of velocity pulsaiton amplitude occurs in such a way that the less is the scale of turbulent pulsations, the less is the distance from the turbulized layer where they attenuate. Only comparatively large-scale turbulent pulsations can penetrate in the laminar region of the current. They create irregular distortion of turbulent zone boundary and intermittent alternation of turbulent and laminar regimes of the current.

Pulsation spectra of wind velocity components are described by the power law. Under neutral thermal stratification they correspond to the law of "minus five thirds" by Kolmogorov-Obukhov and under stable stratification the index is more than 5/3 and fluctuates in the range of 2.1 to 3.5. The increased value of vertical gradient of the mean wind velocity in stably stratified atmosphere does not change the character of spectral density function but moves it over to the region of higher values of spectral density. The second maximum in the energy spectrum in the region of its high frequences (so called Van der Hoven spectrum) attenuates as it moves away from the ground and is observed in the free atmosphere only in the presence of turbulent energy influx at the cost of short gravitational waves decay.